Study on the CO_2 Absorption in Several Types of Amines

by

Khalid Rafaee

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Chemical Engineering Programme
Universiti Teknologi PETRONAS
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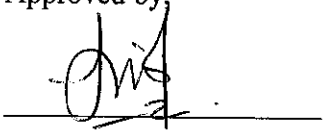
Approved by,



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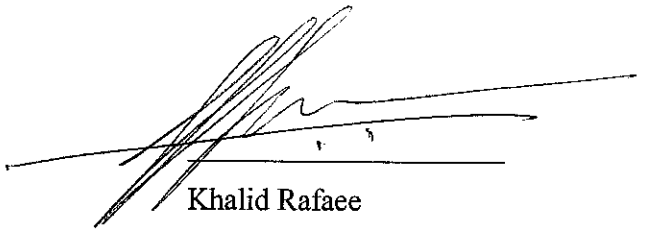

Khalid Rafaee

ABSTRACT

This report detail the findings of the lab experiment of CO_2 gas absorption into amine based solvents. Prior a literature review established mixture of amine solution processes as the most attractive alternative to the most common solvent in industry, secondary amine. On that basis these processes were selected to compare against the secondary amine, Diethanolamine (DEA). As a starting point, understanding the process and operational variables in the industry is an advantage to relate the industrial practices and theoretical values. Those variables could be used as guidance in carrying out this work

The experiment is driven by two issues: The capability of each of the amine solution in CO_2 absorption process and to test the tendency of 'foaming' in all the prepared solvent in this work. The comparison of CO_2 loading in each of the prepared solvent was done by simple mathematical method. The method was used to determine the amount of CO_2 absorbed per 1 milliliter of solvent. The methodology is a must due to the difficulties in fixing the concentration of CO_2 in the feedgas.

Rate of absorption of CO_2 into amine was determined from the gas phase material balance using the measured inlet and outlet gas concentration. The comparison between the two solvents was carried out on the basis of the different concentration and lean solvent flowrate. Theoretically, different flowrate and concentration of solvent will affect the rate of absorption as well as the CO_2 loading capacity. Again, the rate of reaction of the mixture of various amines is slightly lower relatively to the single amine with higher concentration. The foaming tendency tests were carried out in order to test the reliability of each of the prepared solvents. Higher foaming tendency in the solvent can cause the instability in operating the unit. In this work, the mixture of solvent was found not really at the higher risk of foaming. The mixture of 21.83 wt% DEA and 10.23 wt% MEA can be concluded as the most attractive in term of capability to absorb CO_2 as well as the resistance to foaming. More study on this solvent is required especially on the corrosiveness, hydrocarbon loading and reclamation process.

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NOMENCLATURE

δ	Wetted wall film thickness
ρ	Density
τ	Surface exposure time
π	PI
η	Mass transfer coefficient
θ	Mass transfer coefficient parameter
μ	Viscosity

ABBREVIATION

CO_2	Carbon Dioxide
LNG	Liquefied Natural Gas
AGRU	Acid Gases Removal Unit
aMDEA	accelerated Methyldiethanolamine
DIPA	Diisopropanolamine
MEA	Methylethanolamine
DEA	Diethanolamine

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND OF STUDY

Chemical absorption of acid gases by alkanolamines has found application in a wide variety of industries including the natural gas processing and the removal of Carbon Dioxide (CO_2) from synthesis gas in the production of hydrogen or ammonia. With the recognition of CO_2 as a greenhouse gas, another important application of this technology is CO_2 removal from combustion gases at power plants or manufacturing facilities. The technology of treating process gas with alkanolamines in absorption/regeneration systems became popular in the 1930's and has been used successfully since then.

In the Liquefied Natural Gas Processing Plant (LNG), natural gas has to be treated before it can be routed to the Liquefaction Unit (downstream processing unit). One of the treatments is to remove the acid gases from the natural gas stream in order to avoid freezing, corrosion at the downstream equipment and to meet the LNG specification (requirement from the customer).

In typical LNG plant, feedgas (sour gas) enters the bottom of the absorber column in Acid Gases Removal Unit (AGRU) where it is counter currently contacted with lean amine solution (solvent) that enters the column at the top. The simplified Process Flow Diagram can be referred to figure 1.1. The absorber may be a 'trayed' or packed column. As the amine solution travels down the column, it becomes loaded with acid gases and leaves the bottom of the absorber as rich amine (fat solvent). The sweetened gas leaves the top of the column where it is further processed. The fat solvent is heated by the heat exchanger (recover heat from the lean solvent) and fed to the regenerator. In the regenerator, the absorbed acid gases are driven out of

the amine solution. The energy required to regenerate acid gases from solution is provided by a reboiler at the bottom of the regenerator. The flashed off acid gases are normally sent to the other unit such as the Incineration Unit for further processes before they can be released to atmosphere.

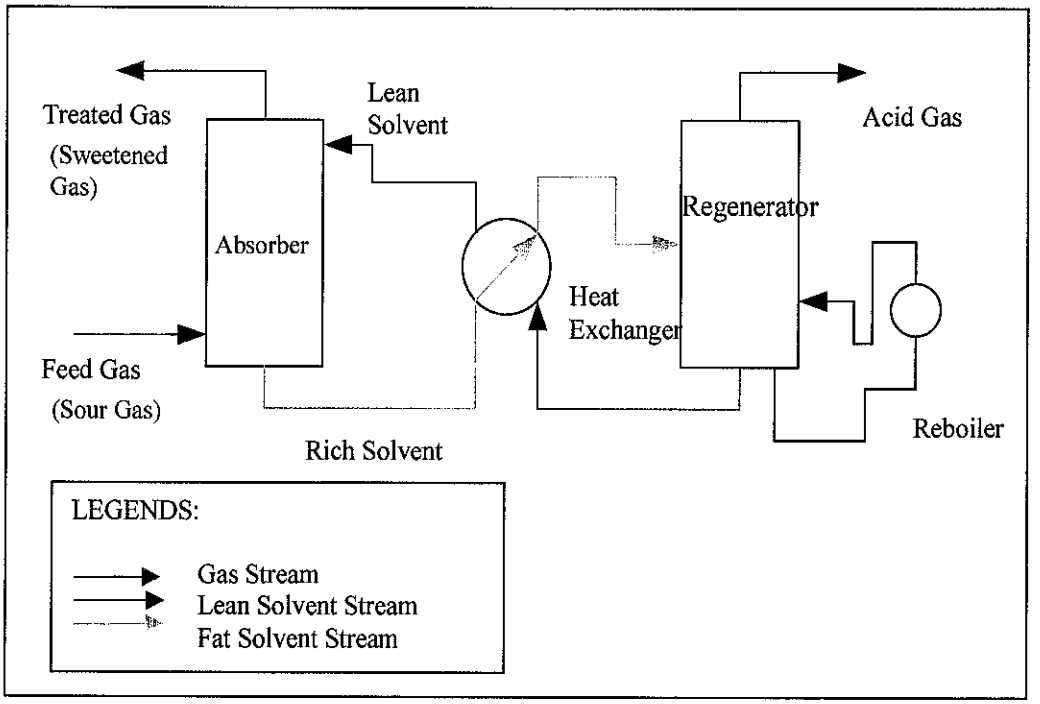

FIGURE 1.1: Simplified Process Flow Diagram of AGRU in Typical LNG Plant

Currently research focuses on the use of new solvents with various compositions to absorb CO_2 more effectively and economically. On top of that, the research should focus on the complexity of that process as well as the variables in controlling the unit. These complexities could be appreciated by considering a typical process flow diagram of this process and which is shown in figure 2.1 in Chapter 2.

For natural gas, typical inlet concentrations of CO_2 vary over a wide range due to the naturally occurring variations in the feed gas found in the reservoir. For instance the CO_2 composition in the inlet gas of PETRONAS Liquefied Natural Gas' Plant (MLNG) and PETRONAS Liquefied Natural Gas DUA's Plant (MLNG DUA) are not equal. Thus the loads to AGRU of both plants are not the same (MLNG and MLNG DUA Data Sheet, 2004). The higher the CO_2 composition in the feed gas, the higher the load of that particular plant. Scope of this study is to obtain the data of

CO_2 uptake capacity in the various solvent with different composition. On top of that, the tendency of 'Foaming' of that particular solvent was tested.

1.1.1 Problem Statement

Most of the LNG Plants in the world are 'Production Driven Plant' (En. Shamsudin Miskon, 2004). The reliability of the plant is very critical. Any unnecessary trip to the plant would cost the company reputation and production losses. One of the contributors in the total trip of the plant is slow response and incapability of the AGRU towards the upset of the plant. The reliability of AGRU itself is mostly depending on its solvent quality.

In some cases, the sudden increase of the load to AGRU has caused an entire plant to be downed. The recovery process might take few days (production to production). Instability of AGRU leaves the entire plant in jeopardy. Sudden increase of the load to AGRU is mainly contributed by tremendous change of CO_2 composition in the feedgas. The problem might not be significant if the plant is in low production mode. Low production of LNG requires low flow of solvent circulation in AGRU. With good quality solvent, the CO_2 uptake would be increased. According to BASF (2002), accelerated Methyldiethanolamine (aMDEA®) could increase the CO_2 uptake up to 53% (from 0.85 to 1.3 mol %) relatively to the existing solvent, Diisopropanolamine (DIPA), which is mainly used in LNG plant. Improvement of solvent quality in term of CO_2 absorption capability might reduce the number of unnecessary trip in LNG plant by increasing the flexibility of its operation as well as its reliability.

Higher demand of LNG as a source of energy worldwide has increased the number of new LNG plants. Nevertheless, some of the existing LNG plants have carried out the 'de-bottlenecking' exercise to meet this higher demand. De-bottlenecking exercise in LNG plant is to enlarge the plant production capacity by improving some of its processing unit. The activity might require some hardware change or just an operating parameters improvement.

One of the best bets is to improve the Gas Treatment System of that particular plant. For instance, Brunei LNG (BLNG) in Lumut, Brunei Darul Salam has done the trial of swapping the solvent in AGRU in order to increase the total plant production. The test was done successfully and to date all of their solvent in AGRU of all the production trains have been changed. Need for the better solvent is very significant in this case. Due to the limitation on the piping system in the AGRU, has limited the amount of solvent flow and consequently affect the amount of treated gas as well as the end product. Newly changed type of solvent should treat higher flow of feedgas with the similar amount of solvent flowrate before. Retaining the solvent flowrate with relatively higher production would increase the plant efficiency and the operating cost. Meaning that, lower energy needed for certain amount of production.

Some of LNG Plants experience increasing CO_2 composition in the feedgas over time. The higher the CO_2 composition in the feedgas, the higher amount of solvent needed to treat it. At some extent, the LNG production has to be brought down in order to overcome this problem. Again, the improvement on AGRU is highly required in this case especially on the quality of its solvent. One of the options is to change the existing solvent to a new type and concentration of solvent. With higher CO_2 loading solvent, eliminating the constraint of maintaining or may be increasing the production would be possible. For example, since 2003, sour gas fields F13 and B11 was respectively introduced to MLNG and MLNG Dua plants in addition to the existing gas fields. During the period after year 2003, other smaller gas fields (G7, B12, F29, S. Clastic, D12, Beryl and Laila) were lined up to MLNG Dua. As the forecast future feedgas contains much higher CO_2 concentrations than the current feedgas the incorporation of these fields will result in an increased load on the AGRU (M.A, Rithaudeen, 2003).

Sudden change in CO_2 composition or load to the unit would induce 'foaming' in the Absorber or Regenerator Column. This phenomenon occurs when the falling solvent liquid start to generate foam on the trays due to various reasons. This foam would restrict the falling solvent flow and cause it to accumulate on the trays, one after another. Consequently, level on the trays would rise up to the top of the column. At this point of time, the entire plant would be downed either automatically or manually by the operators. The rising level takes about 1 to 2 minutes to reach the

top of the column (Waheeda W, 2001). This problem is almost unstoppable. At some extent, some of the LNG plant has to reduce the production for few weeks to overcome the problem. The best option is to replace the solvent with the one that relatively 'tougher'. In this work, the tendency of solvent to 'foaming' is tested with various condition and quality. Philosophy of this study not only to determine the capability of the solvent as well as the 'foaming' tendency in the system.

1.1.2 Objectives and Scope of Study

This work is driven by three objectives;

i. To determine the CO_2 absorption capacity of each of the prepared amine solution (solvent). The CO_2 absorption capacities of these solutions were measured from the ability of the solution to absorb CO_2 in term of quantity as well as the equilibrium time. Rate of absorption was determined from the gas phase material balance using the measured inlet and outlet gas concentration. CO_2 gas absorption rates are measured in a region where the flow rate of carbon dioxide could be quantified.

ii. To quantify the effectiveness of blended amine solution (MEA and DEA). The absorption rates of CO2 in the solution have been measured in fat and lean solvent with a Wetted Wall Column.

iii. To determine the ability of the prepared solvents in sustaining the stable condition from 'foaming' due to the various testing condition.

The scope of study addressed in this document includes:

i. To study the effect of CO_2 absorption into various type of solvents at different parameters.

ii. Preliminary research on the Physical and Chemical properties of the amines. Research on the Amine solvent improvement (Blended Amines solvent with water, physical absorber or accelerator)

iii. Review on the industrial practices on the operation of AGRU as well as available internal and external variables (operating). Scope definition and design of operational and equipment improvement.

iv. Brief outline on the facilities and experimental apparatus (equipment verification). To set up the simple experimental apparatus using the existing apparatus in Unit Operation Lab. Some modification on the apparatus in order to optimize the experiment

v. To provide some calibration method prior to the experiment. This activity is essential to ensure the consistency of all the obtained data. All the flowmeters in this work were calibrated in accordingly with the requirement of the typical experiment.

vi. To construct the sequential methodology in carrying out the experiment. The through check on all the apparatus is crucial in order to maintain the safety and reliability of the experiment.

vii. Analysis and interpretation of experimental data. Develop the correlation between the type and concentration of solvent with the rate of CO_2 absorption and tendency to 'foaming'.

viii. Conclusions and recommendations.

CHAPTER 2
LITERATURE REVIEW

2.1 THEORY OF CO_2 ABSORPTION IN ALKANOLAMINES

2.1.1 Definition of the Absorption Process.

Absorption is one of the types of separation processes. Absorption process occurs when two contacting phases are a gas and a liquid react chemically or physically. A solute ***A*** or several solutes are absorbed from the gas phase into a liquid phase in absorption. This process involves molecular and turbulent diffusion or mass transfer of solute ***A*** through a stagnant non-diffusing gas ***B*** into a stagnant liquid ***C***. (Geankopolis, 1993)

2.1.2 Brief History of the Alkanolamines Solvent in the Absorption Process.

Initially, Triethanolamine (TEA) was the first to become commercially available. As other members of the Alkanolamine particularly the primary and secondary amines were introduced into the market, they achieved general acceptance for gas purification. It is reported that until the 1970's, Monoethanolamine (MEA) was the amine first considered for any sweetening application. (Bishnoi S, 2000)

Then, in the 1970's, switching from MEA to Diethanolamine (DEA) yielded favorable results. Later, during mid 80's, Methyldiethanolamine (MDEA) and Diglycolamine (DGA) have gained popularity for application in new sweetening plants. Nevertheless, another Alkanolamine process is also replacing MEA treating plants during this period. In 1963, Shell Sulfinol Process was introduced to the industry and to date it is reported that approximately 130 North American and 200

worldwide units have been licensed. The Sulfinol process is the mixture of Sulfolane (Tetrahydrothiophene Dioxide), water and either DIPA or MDEA. It is licensed by Shell and known by these commercial names:

i. Sulfinol-D, which is a mixture of Sulfolane, water and DIPA

ii. Sulfinol-M, which is a mixture of Sulfolane, water and MDEA

Development of Alkanolamines as absorbents for acidic gases started as early as 1930's. Before then, carbonate processes such as Na_2CO_3 were used for natural gas purification. Amines are categorized as being primary, secondary or tertiary depending upon the degree of substitution of the central nitrogen by organic groups. Primary amines are chemically stronger bases than the secondary amines; hence they are more reactive towards CO_2 and will form a stronger bond with the acid gases. The rate of reaction for CO_2 decreases with the substitution on the nitrogen group such that primary amines react faster than secondary and tertiary amines. Furthermore, primary amines demonstrate higher reactivity by exerting a lower acid gas vapor pressure than the secondary amine at equal loading.

Only recently, MDEA blends with accelerators have gained a larger share in the market for deep CO_2 removal. The presence of the accelerator/promoter made the reaction rate relatively faster than that of aqueous MDEA alone. Common promoters used are MEA, DEA or 1,4-diethylenediamine (DEDA, a Cyclic Diamine usually referred as Piperazine, PZ). Many companies are offering their own version of formulated MDEA, e.g. BASF aMDEA, OPTIMAL Ucarsol, SHELL ADIPX, ATOFINA MDEA-ACT, and HUNTSMANN JEFFTREAT.

2.1.3 Amine Solvent Chemistry

Naturally, an acid gases such as CO_2 when dissolved in an aqueous medium, will dissociate to form a weak acid. The amines are weak organic bases. In general, the acid gas and amine base will combine chemically to form an acid base complex (salt), thus removing the acid gas from the process stream.

The general reactions between an amine and H2S and CO_2 occur according to the following equations, where R denotes either a primary, secondary or tertiary amine:

$$2RNH_2 + H_2S \leftrightarrow (RNH_3)_2S \quad \text{(fast)} \tag{2.1}$$

$$(RNH_3)_2S + H_2S \leftrightarrow 2RNH_3HS \quad \text{(fast)} \tag{2.2}$$

CO2 reacts predominantly via the reaction below, forming a carbamate with primary and secondary amines.

$$2RNH2 + CO_2 \leftrightarrow RNHCOONH_3R \tag{2.3}$$

Tertiary amines, unable to form carbamates, react via the bicarbonate reactions below. The slow CO2 reaction with water controls the rate of absorption of CO2 into a tertiary amine.

$$2RNH2 + CO_2 + H_2O \leftrightarrow (RNH_3)_2CO_3 \quad \text{(slow)} \tag{2.4}$$

$$(RNH_3)_2CO_3 + CO_2 + H_2O \leftrightarrow 2RNH_3CO_3 \quad \text{(slow)} \tag{2.5}$$

The reaction of H2S is nearly instantaneous with all amines. The reaction rate of CO2 is relatively slower and widely variable for different amines. The salts formed are easily dissociated in the thermal regeneration process. If a stronger acid than H2S or CO2 reacts with the amine, an unregenerable salt will be formed. The bond formed is too stable to be broken down under normal regeneration and such salts are appropriately named "heat stable salts (HSS)". Apart from HSS, contaminants build up from solvent degradation products (thermal or chemical) and corrosion products. These contaminants share the common physical characteristic of low volatility and increase the corrosion potential of the solution. A simplified summary of the degradation characteristics of gas treating processes, related to selected gas constituents is shown in the table below.

2.2 REACTION OF CO_2 WITH PRIMARY AND SECONDARY AMINE.

Caplow et al. (1968) presented a mechanism for carbamate formation involving the formation of an intermediate zwitterion (a locally ionic, net neutral molecule). His proposed mechanism showed a hydrated amine group (with a hydrogen on the amine with weak bond to the oxygen in water) forming the zwitterions. The deprotonation step then referred to the separation of a hydronium ion and the carbamate. Danckwerts et al. (1979) introduced this mechanism into the chemical engineering literature, and Blauwhoff et al. (1984) showed that this mechanism reconciled much of the data in the literature, especially for DEA and other secondary amines. Although Danckwerts and other investigators after him consider the zwitterions species to be attacked by base which extracts a proton in their work, they ignore the suggestion that the amine group may be hydrated before forming the zwitterions.

2.2.1 Literature Data for MEA.

Blauwhoff et al. (1984) reviewed the data available for the reaction of CO_2 with MEA and concluded that the data is consistent with the other's works. All the other investigators found a first order dependence for the reaction rate of CO_2 with MEA. And Blauwhoff et al. (1984) concluded that the rate expression of Hikita et al. (1977) fits the data extremely well over the range of 5 – 80 °C.

$$\text{Log}_{10}\, k_2 = 10.99 - (2152/T) \qquad (2.6)$$

k_2 is in unit of m^3/kmole. Barth et al. (1986) studied the reaction rate at a later date, and found that the results compared very well with the previous literature data. Although there is general agreement regarding the activation energy, order and absolute value of the kinetics of CO_2/MEA kinetics, there are a few points of concern regarding the type of data and the temperature as well as the amine concentration. None of the investigators have studied a wide temperature range including the temperature range usually seen in an absorber column (Bishnoi, 2000). No work has been done at flue gas conditions with 5M amine and in partially loaded solution (Bishnoi, 2000). Following are the literature data on the reaction between CO_2 and MEA which is mostly from Blauwhoff et al., 1984)

2.2.2 Literature Data for DEA

Due to its popularity, the literature review on data covering DEA is extensive. However, there is general disagreement as to the order and rate of reaction of DEA. Recently, Crooks et al. (1989) has questioned the validity of the previous obtained data from the previous experiment. The disagreement due to the equilibrium constant for the deprotonation step which is stronger than expected value. Several researchers point out that the previous expression does not explain the data taken from the absorption of CO_2 into DEA, therefore should not be completely valid for this case.

As with some other amine base solution, the rate constant at stripper temperature are not really known. Nevertheless, it is quite possible that desorption process is occurred likely more at the temperature of 120°C.

2.2.3 Reaction of CO_2 with Hindered Amines

Exxon and others have performed a great deal of work in the field of acid gases absorption with hindered amines. This includes a number of bench scale experiments and pilot plant tests from which there have been a number of publications, patents as well as papers in various journals. FLEXSORB SE and FLEXSORB PS are two proprietary gas testing agents that Exxon has developed for selective removal of acid gases.

Hindered amines are generally primary or secondary amines that do not form a stable carbamate. Hindered amines typically have a bulky alkyl group attached to the amino group. It can be a primary amine in which the amino group is attached to a tertiary carbon atom or secondary amine in which the amino group is attached to the tertiaty carbon atom (Sartori, 1983).

Generally, the hidered amines can be classified as either moderately hindered or severely hindered amines. The moderately hindered amines are normally used for bulk non-selective removal of acid gases while the severely hindered amines are normally be used to remove the selective acid gases such as H_2S.

Primary and secondary amines are limited in their capacity to absorb CO_2 because of their formation on carbamate. Thus the stoichiometry of the reaction limits the amount of CO_2 that can be absorbed. Tertiary amine on the other hand, exhibit greater capacity to absorb CO_2 but have lower rates of absorption relatively to the primary and secondary amines. This is because tertiary amines absorb CO_2 as bicarbonate rather than carbamate. Moderately hindered amines are characterized by forming carbamates of low to intermediate stability. The reaction with CO_2 proceeds mainly through the production of bicarbonate. Carbamate reversion to bicarbonate is also a significant reaction. Thus, these moderately hindered amines have a high thermodynamic capacity that approaches the ability of tertiary amine with higher.

CHAPTER 3
METHODOLOGY/PROJECT WORK

3.1 IDENTIFICATION OF EXPERIMENTAL APPARATUS AND METHODOLOGY

Figure 3.1 shows the wetted wall column used in this work. The wetted wall used is an Armfield's Wetted Wall Gas Absorption Column. The Wetted Wall Column was used to determine gas/liquid mass transfer coefficient as well as the rate of absorption. The wetted wall column was constructed from a glass with a well defined height (900mm) and internal diameter (32mm) and a characteristic liquid film mass transfer coefficient similar to that of a packed tower. Figure 3.2 show the overall diagram of the apparatus used in this study to obtain rate of absorption and mass transfer coefficient of CO_2 in the amines solution.

In the typical experiment, the experiment is the absorption of oxygen into oxygen free water. In this system the solubility and enthalpy of solution are small and by saturating the inlet air with water, humidification effects are eliminated. Thus it is possible to maintain reasonably isothermal conditions throughout the column. Consequently, some modification was made to the apparatus prior to the experiment.

In this work, rate of absorption was determined from the gas phase material balance using the measured outlet gas concentration. CO_2 gas absorption rates are measured in a region where the flow rate of carbon dioxide could be quantified. The device to measure the outlet gas concentration in this work is Yokogawa's Infrared Gas Analyzer, IR 200. To monitor the reaction in the column, the temperature at column's wall is measured part by part.

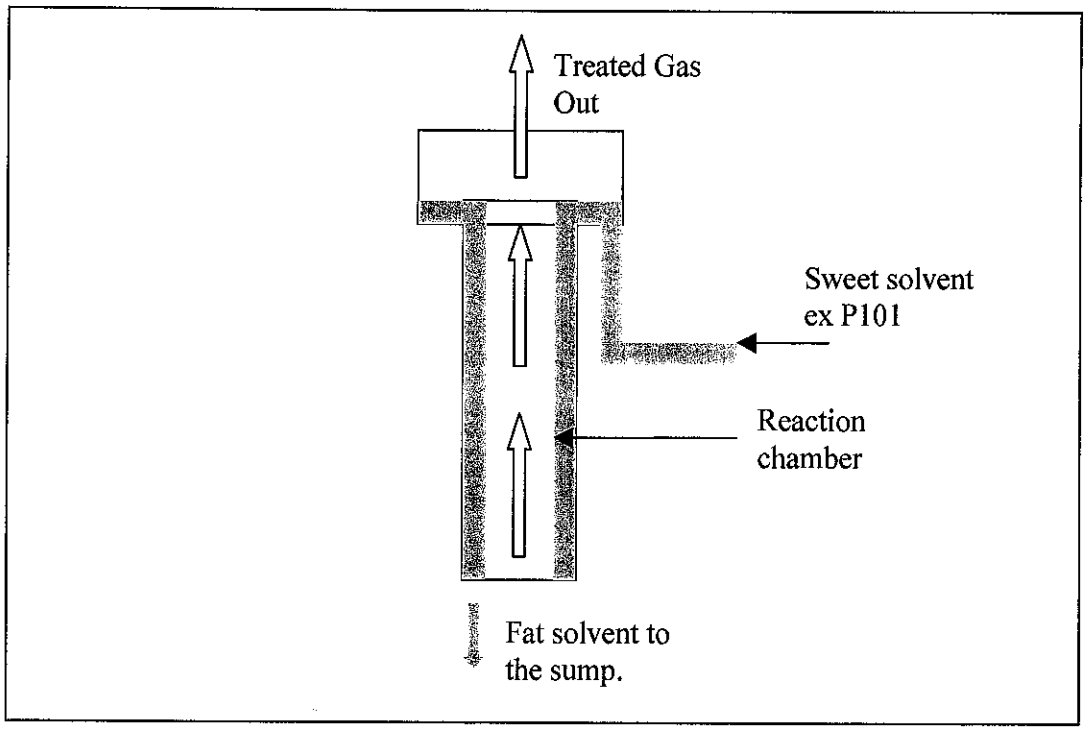

FIGURE 3.1: Detailed column diagram

Flow from two gas cylinders are controlled by the independent gas regulators in order to get the right blend of CO_2 and N_2 inlet gas to the column. The inlet gas concentration is blended based on the CO_2 content which is in the range of 0% to 20% volume (measurable range of the analyzer). In order to stabilize the temperature at the inlet of the column along the experiment, both of the gases, CO_2 and N_2 are routed to the heat exchanger, E 101 as in Figure 3.2.The temperature of the inlet gas is controlled at the same temperature as the wetted wall as possible in order to minimize the error in the experiment as well as to maintain the consistency of the obtained data.

After the heat exchanger, the blended gas is sent to the wetted wall column where it is contacted with the amine solution or sweet solvent. Total pressure used in this work varied from 1 to 1.5 atm. In the wetted wall, a portion of CO_2 gas will be transferred from the gas phase to the liquid phase.

The gas exits at the top of the column (Treated gas) are routed to the IR CO_2 Analyzer for experimental data. Amount of CO_2 gas is measured in percent volume.

The experiment would be started by establishing the blended gas flow to the column and consequently to the analyzer. The adjustment on the CO_2 and N_2 gas cylinders would be required in order to obtain the measurable CO_2 content in the feed gas. This predetermined concentration of the feed gas will be used as a reference throughout this experiment.

The amine solution (lean solvent) is kept in the reservoir, T 101 under 'N_2 blanket' to get rid of air contamination. The reservoir, T 101 capacity is approximately 40 liters. To establish the solvent flow into the system, Lean solvent flow regulator, FC 101 is crack opened prior to the starting up of Feed Pump, P 101. The flow regulator is used to control the lean solvent flow to the Wetted Wall at predetermined flow. The measurable flow range is from 20 to 280 mL/min (corrected to water flow). The lean solvent flow rate used in this work is around 200 to 280 mL/min (corrected to water flow). The flowrate of the solvent is assumed to be a function of solution viscosity and the flow meter reading. The calibration of this flow meter would be discussed in the next section.

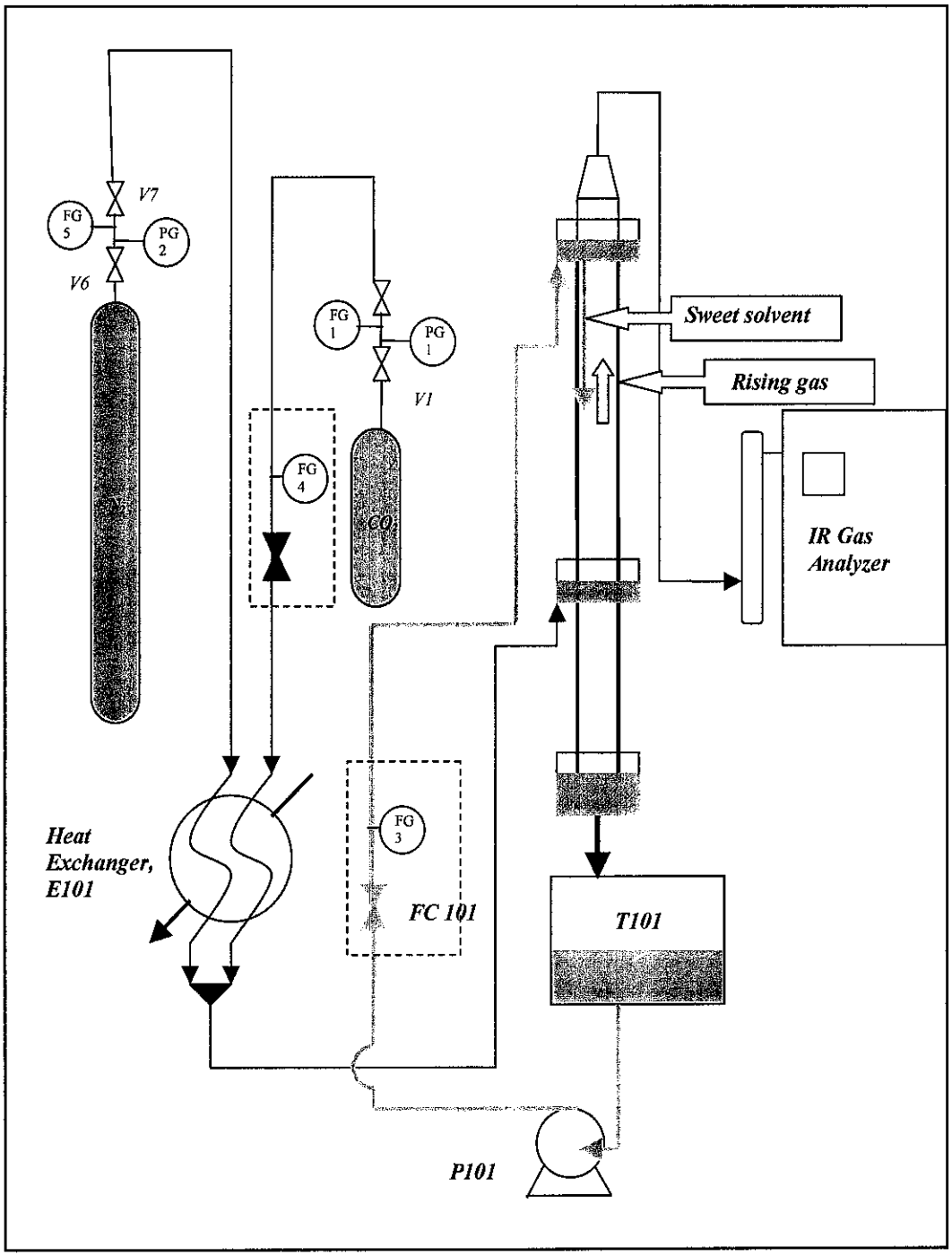

FIGURE 3.2: Overall flowsheet of equipment.

3.2 CALIBRATION OF THE FLOWMETER

The flow meter used in this work was originally calibrated in water. Accurate measurement of the lean solvent flow at any particular time during the experiment is crucial in order to obtain the relationship between the Lean solvent flow and the gas flow. The volumetric flowrate of the lean solvent ex P 101 is regulated via FC 101 at the determined value. And the volumetric flowrate of the lean solvent over time is checked against the volumetric scale on the calibration tank to obtain the relationship between the water and each of the solvent used in this work. Figure 3.3 show the experiment set up in obtaining the correlation of the Lean solvent flowrate and the flow meter reading. Theoretically, the lean solvent flowrate is a function of viscosity and the flow meter reading. All the obtained time to fill the Calibration cylinder at the predetermined volume is tabulated in order to get the lean solvent flow rate. The graph of lean solvent flow rate versus the flow meter reading is plotted to attain the correlation of the flowrate and the meter reading.

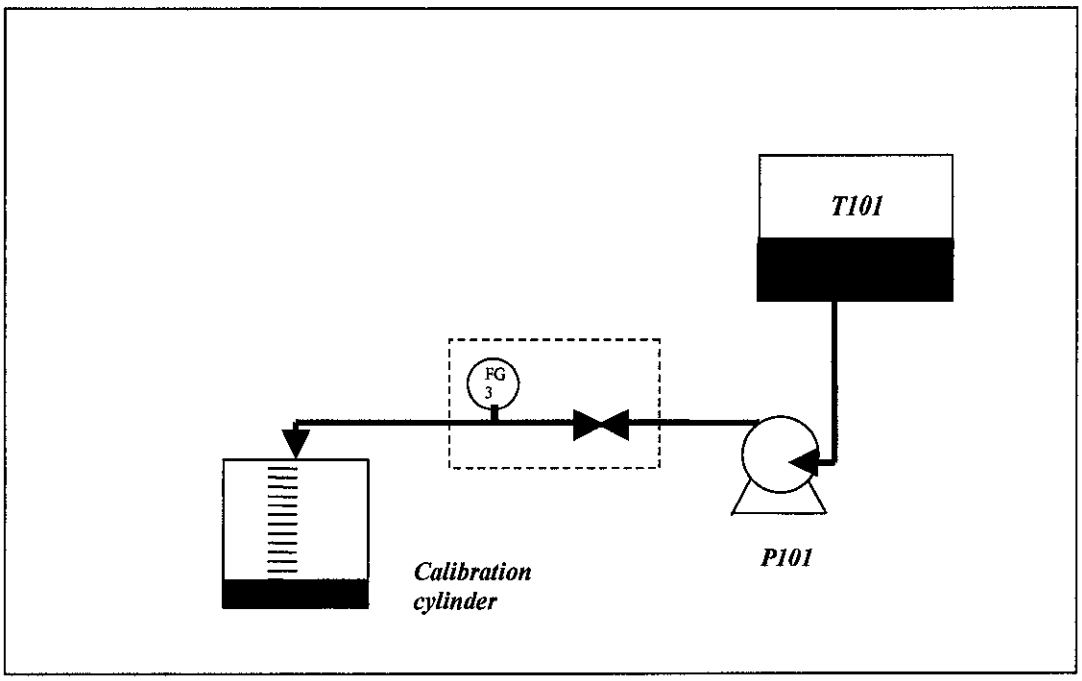

FIGURE 3.3: Experimental set up of flow meter calibration.

3.3 TEMPERATURE TAKE OFF POINT

The absorption process of the CO_2 by various type of amines is an exothermic reaction, thus heat will be released during the process. Figure 3.4 shows the temperature take off point in this work. The device used in obtaining the temperature is Carlsen Infra red Temperature Probe.

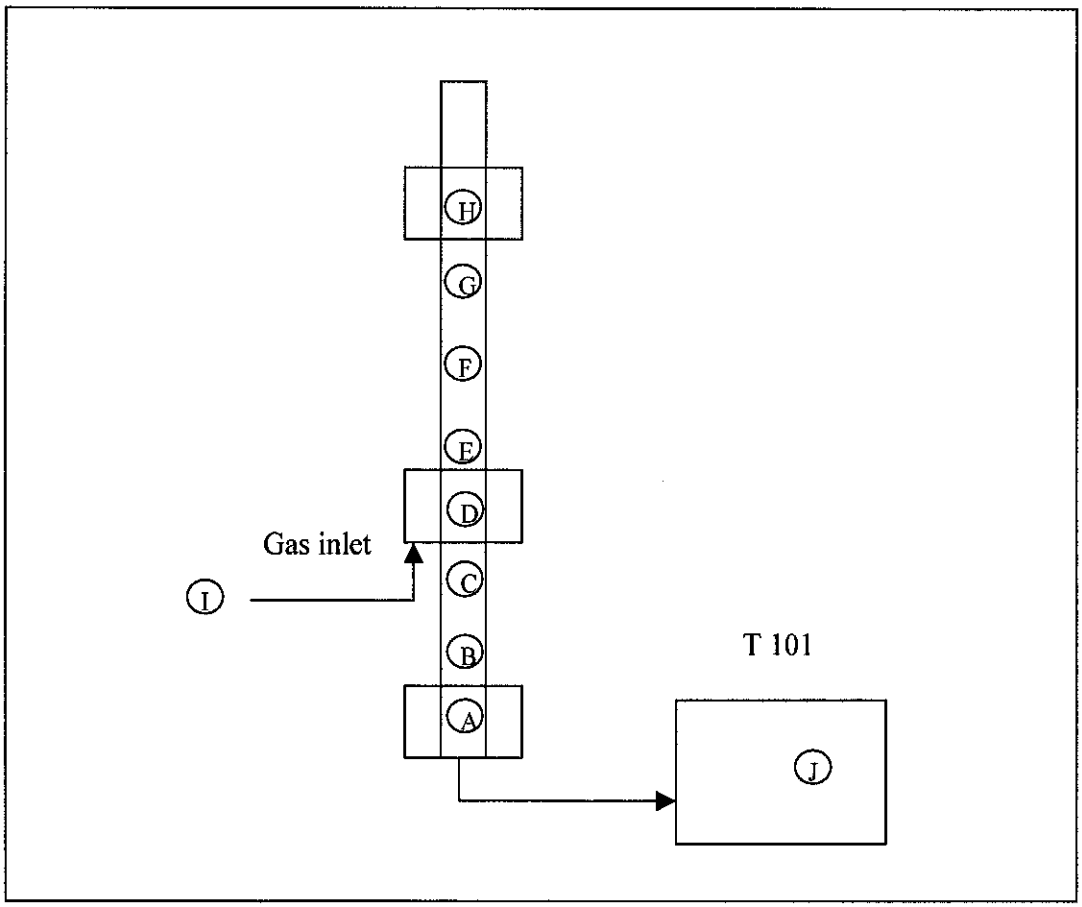

FIGURE 3.4: Temperature take off points

3.4 RATE OF ABSORPTION AND SOLVENT FILM MASS TRANSFER COEFFICIENT

In this work, rate of absorption is determined from the gas phase material balance using the outlet gas concentration via Yokogawa's Gas Analyzer, IR 200. The concentration of CO_2 is checked and recorded over 1 minute interval. The characteristic of CO_2 absorption process in the Wetted Wall Column can be observed by plotting the graph of IR 200 readout over time.

The liquid film mass transfer coefficient of the wetted wall column was measured by Mshewa (1995) and Pacheco (1998). Pacheco's model relies on solving the momentum balance for a falling film to determine film thickness (δ) and surface velocity. The film thickness (δ) of the falling solvent liquid on the wall of the column is calculated by using the following equation:

$$\delta = [(3\mu Q) / (\rho g W)]^{1/3} \qquad (3.1)$$

Where W is the wetted wall perimeter length, μ is viscosity of the solvent, Q is the volumetric flowrate of the solvent, ρ is the density of the solvent and g is the gravitational force. Meanwhile the surface velocity (u_s) can be calculated based on the following equation:

$$u_s = (\rho g \delta^2) / (2 \mu) \qquad (3.2)$$

And surface contact time, τ

$$\tau = l / u_s \qquad (3.3)$$

where l is the length of contactor

The other equation developed by Bishnoi (2000) is mass transfer coefficient parameter, η.

$$\eta = D \tau / \delta^2 \qquad (3.4)$$

From this parameter, the value of another parameter (θ) is obtained.

$\theta = 0.7857\exp(-5.121\ \eta) + 0.1001\exp(-39.21\ \eta) + 0.036\exp(-105.6\ \eta) + 0.0181\exp(-204.7\ \eta)$; for $\eta > 0.01$

$\theta = 1 - (\eta/\pi)^{1/3}$; for $\eta < 0.01$

Finally the value of solvent film mass transfer coefficient, $k^{o}_{L.A}$ is calculated by the following equation:

$$k^{o}_{L.A} = (Q/a)(1 - \theta) \qquad (3.5)$$

Where **a** is the Wetted Wall specific contact area.

In order to minimize the resistance to the rising gas in the Wetted Wall, the overall flow rate of the lean solvent is ranged from 200 ml/min to 280 ml/min. to prevent the equipment damage, the experiment is carried out at the very low pressure and it's controlled by the CO_2 and N_2 gas regulator. The regulators are used to blend the both gases at the right concentration.

3.5 EXPERIMENTAL METHODOLOGY OF OBTAINING THE PREDETERMINED CONCENTRATION (WEIGHT PERCENT) AND AMOUNT (VOLUME) OF THE SOLVENT MIXTURE.

3.5.1 Minimum Inventory of the Solvent Mixture

The experiment will be carried in various concentration of amine. Proper calculation and sequencing of the amine mixture throughout the experiment in order to run the experiment smoothly. As per previous discussion, huge amount of amine is required to blend with water or other type of amine to make up a solvent solution due to the relatively huge of the tank size.

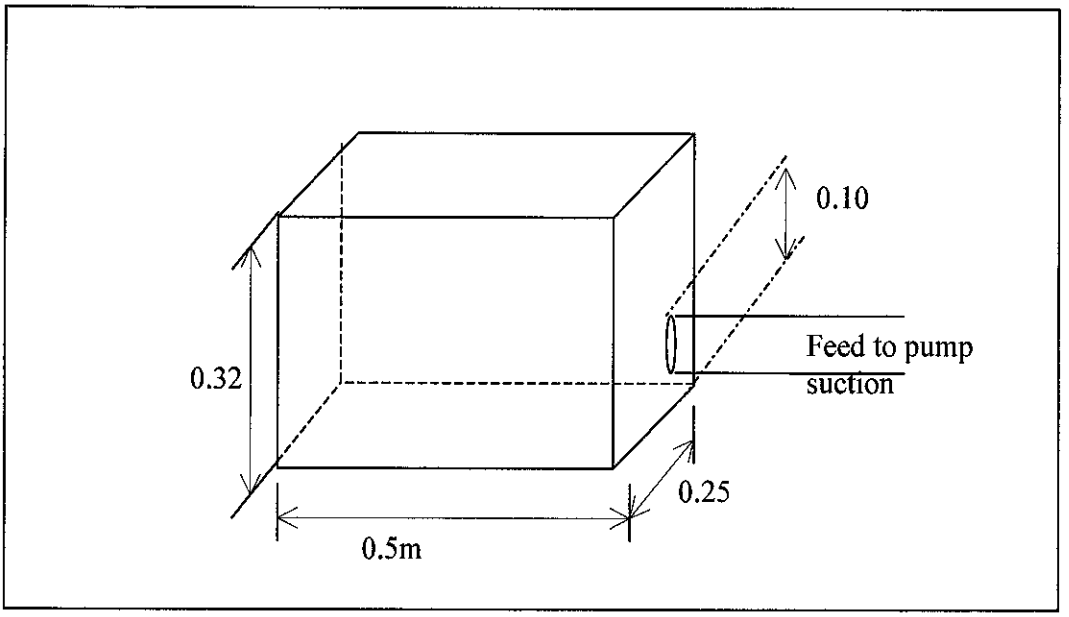

FIGURE 3.5: The solvent sump, T101.

Total volume of the sump = 0.5m (l) x 0.25m (w) x 0.32m (h)

$= 0.04\ m^3$

= 40 liters (3.6)

Distance between the base of the sump to the highest point of the P 101 suction, h_s

= 0.1 m

Minimum level of solvent in the sump during the experiment

$= [0.5 \times 0.25 \times 0.1]\ m^3$

$= 0.0125\ m^3$

= 12.5 liters (3.7)

Total length of the solvent line to/from the wetted wall column from/to sump

= 3 m

Average diameter of the solvent line = 15 mm

Total inventory of solvent in the line

$= (\pi D^2 L)/ 4$

$= 0.00053\ m^3$

$= 0.53$ liters (3.8)

Solvent inventory in the wetted wall column = 0.5 liters (3.9)

Total inventory of the solvent mixture prior to commissioning of experiment

= (10.2) +(10.3) + (10.4)

= 13.53 liters

= 16 liters (with about 15% safety margins)

Note: Operating the equipment below this minimum inventory of the solvent mixture prior to the starting up of the experiment might damage the circulation pump.

3.5.2 Solvent Management.

In order to ensure the experiment could be carried out smoothly, the proper management of the solvent is essential. The predetermined amount of amine is blended with water to make up the desired solvent solution. The general equation for this calculation is drafted below:

Desired wt % of amine in the solvent mixture

$= [M1/(M1 + M2)] \times 100\%$ (3.10)

Where M1 is the mass of the amine and M2 is the mass of water.

Sample calculation of the solvent mixture:

Mass of DEA per 1 liter of solution.

$= 1\ \text{liter} \times (1\ m^3/1000\ \text{liter}) \times 1090\ kg/m^3$

$= 1.090$ kg

Mass of MEA per 1 liter of solution.

= 1 liter x (1 m^3/1000 liter) x 1020 kg/ m^3

= 1.020 kg

i. Preparation of 5 liters DEA into 13 liters water

= {(5 x 1.090)/ [(5 x 1.090) + (13 x 998)]}x 100 wt %

= 29.58 wt % DEA

ii. Preparation of 5 liters DEA into 15 liters water

= {(5 x 1.090)/ [(5 x 1.090) + (15 x 998)]}x 100 wt %

= 26.69 wt % DEA

iii. Preparation of 5 liters DEA into 17 liters water

= {(5 x 1.090)/ [(5 x 1.090) + (17 x 998)]}x 100 wt %

= 24.31 wt % DEA

iv. Preparation of 5 liters DEA and 1.5 liters MEA into 17 liters water

= {(5 x 1.090)/ [(5 x 1.090) + (17 x 998) + (1.5 x 1.02)]}x 100 wt %

= 22.76 wt % DEA and

= {(1.5 x 1.020)/ [(5 x 1.090) + (17 x 998) + (1.5 x 1.02)]}x 100 wt %

= 6.39 wt % MEA

v. Preparation of 5 liters DEA and 1.5 liters MEA into 17 liters water

= {(5 x 1.090)/ [(5 x 1.090) + (17 x 998) + (2.5 x 1.02)]}x 100 wt %

= 21.83 wt % DEA and

= {(2.5 x 1.020)/ [(5 x 1.090) + (17 x 998) + (2.5 x 1.02)]}x 100 wt %

= 10.21wt % MEA

TABLE 3.1: Solvent mixture of the experiment.

Solution	Volume of DEA in the solution, m^3	Mass Of DEA in the solution, kg	Volume of MEA in the solution, m^3	Mass Of MEA in the solution, kg	Volume of water in the solution, m^3	Mass Of water in the solution, kg	Concentration of DEA in the solution, wt%	Concentration of MEA in the solution, wt%
1	5.00	5.45	0.00	0.00	13.00	12.97	29.58	0.00
2	5.00	5.45	0.00	0.00	15.00	14.97	26.69	0.00
3	5.00	5.45	0.00	0.00	17.00	16.97	24.31	0.00
4	5.00	5.45	1.50	1.53	17.00	16.97	22.76	6.39
5	5.00	5.45	2.50	2.55	17.00	16.97	21.83	10.21

CHAPTER 4
EXPERIMENTAL RESULT AND DISCUSSION

4.1 FLOW METER CALIBRATION.

The flow meter (rotameter) was calibrated prior to the experiment. Existing flow meter is calibrated for water (typical experiment). In order to obtain the accurate flow for lean solvent to the wetted wall, the flow meter required a calibration for each of the solvent solutions in this work.

4.1.1 29.6 wt% DEA Solution

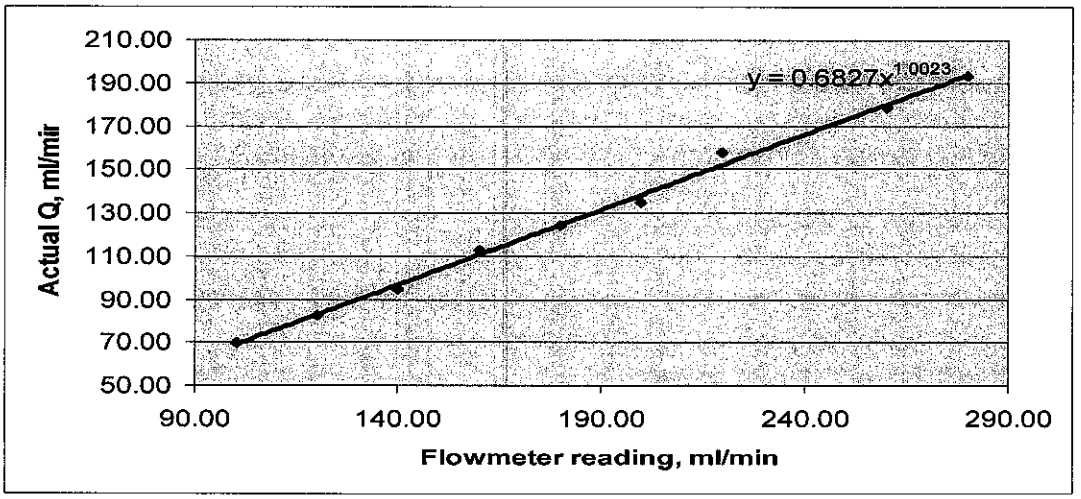

FIGURE 4.1: Actual Q versus flowmeter reading of 29.6wt% DEA Solution

Following is the correlation between the actual solvent flow and the flowmeter reading:

$$Q_{DEA1} = 0.6827\ Q_{FM}^{1.0023} \qquad (4.1)$$

Where Q_{DEA1} is the actual flow in this case and Q_{FM} is the flowmter reading.

4.1.2 26.7 wt % DEA Solution

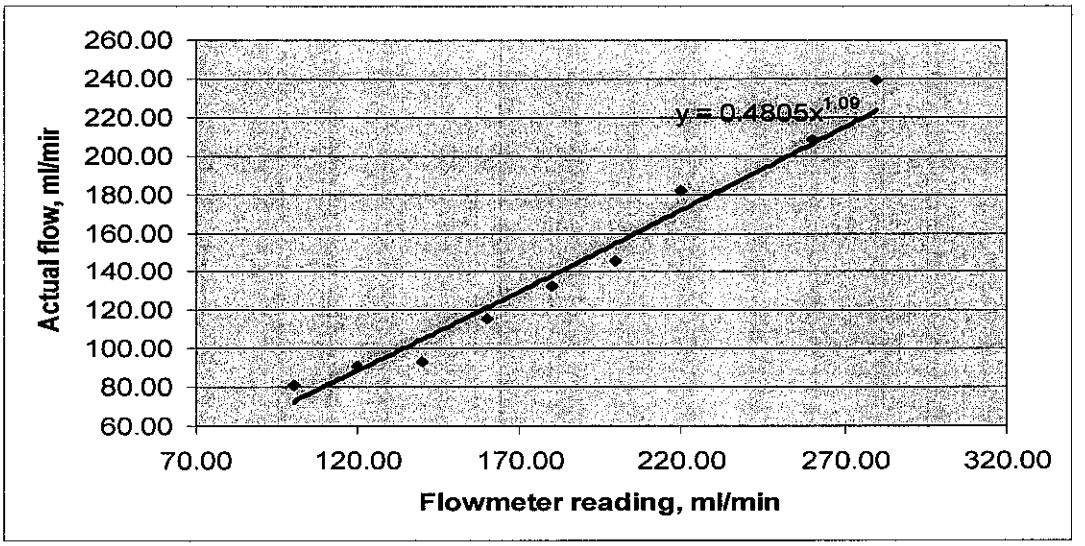

FIGURE 4.2: Actual Q versus flowmeter reading of 26.7 wt% DEA Solution

Following is the correlation between the actual solvent flow and the flowmeter reading:

$$Q_{DEA2} = 0.4805\ Q_{FM}^{1.09} \qquad (4.2)$$

Where Q_{DEA2} is the actual flow in this case and Q_{FM} is the flowmter reading.

4.1.3 24.3 wt % DEA Solution

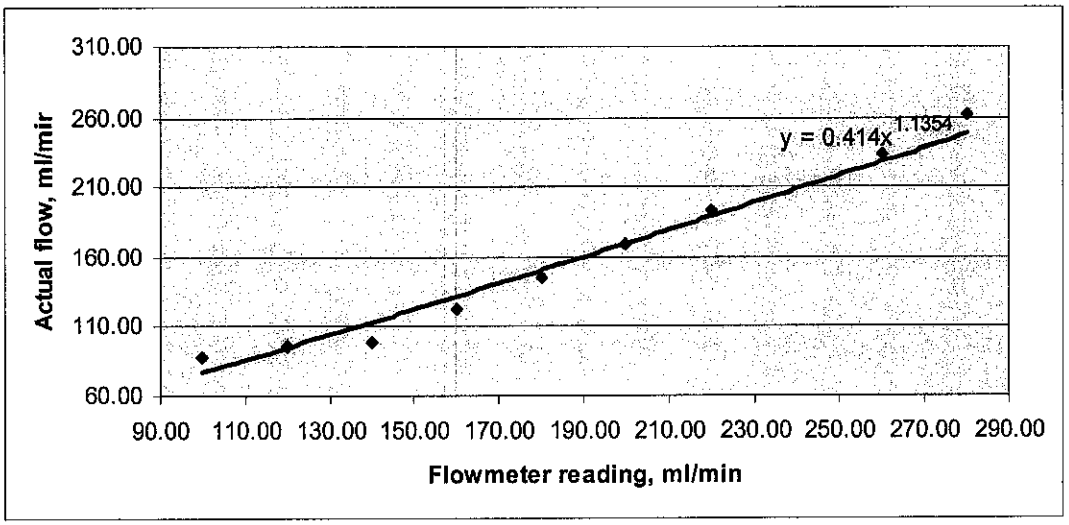

FIGURE 4.3: Actual Q versus flowmeter reading of 24.3 wt% DEA Solution

Following is the correlation between the actual solvent flow and the flowmeter reading:

$$Q_{DEA3} = 0.414\ Q_{FM}^{1.1354} \qquad (4.3)$$

Where Q_{DEA3} is the actual flow in this case and Q_{FM} is the flowmter reading.

4.1.4 22.76 wt % DEA and 6.39 wt% MEA Solution

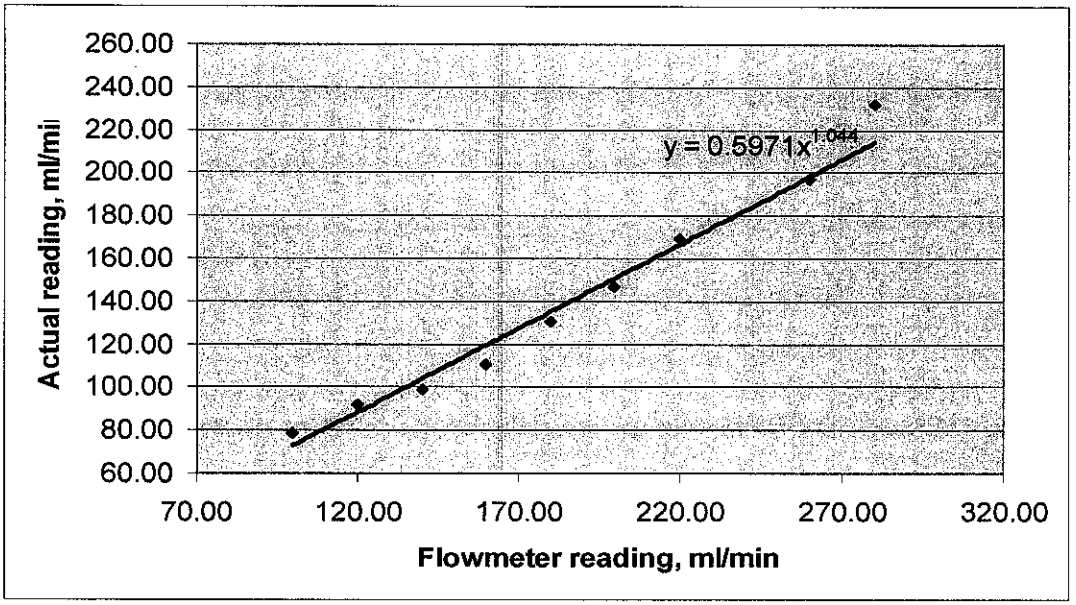

FIGURE 4.4: Actual Q versus flowmeter reading of 22.76 wt % DEA and 6.39 wt % MEA solution

Following is the correlation between the actual solvent flow and the flowmeter reading:

$$Q_{MIX1} = 0.5971\ Q_{FM}^{1.044} \qquad (4.4)$$

Where Q_{MIX1} is the actual flow in this case and Q_{FM} is the flowmter reading.

4.1.5 22.83 wt % DEA and 10.23 wt% MEA Solution

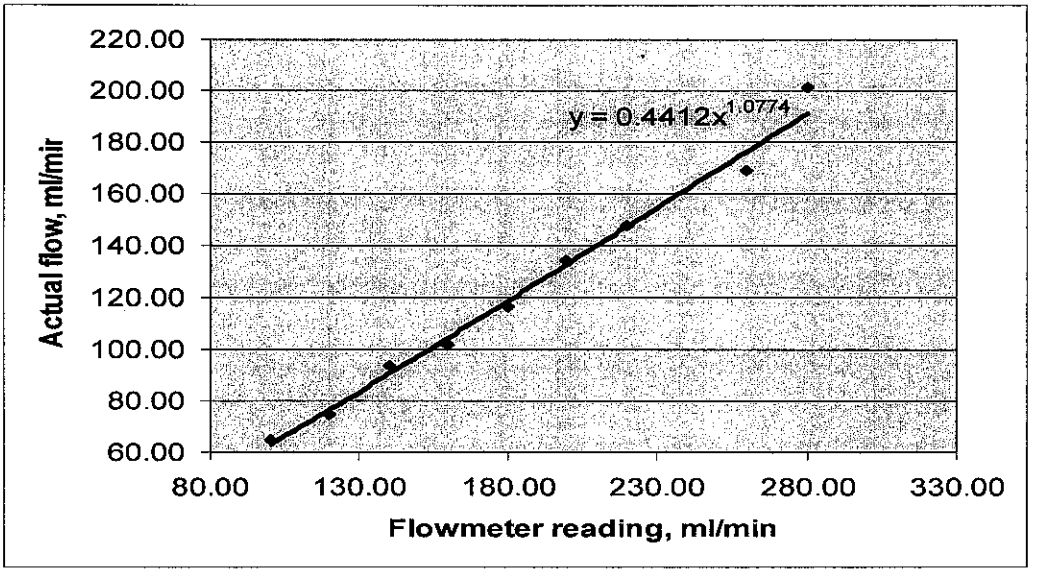

FIGURE 4.5: Actual Q versus flowmeter reading of 21.83 wt % DEA and 10.23 wt % MEA solution

Following is the correlation between the actual solvent flow and the flowmeter reading:

$$Q_{MIX2} = 0.4412\ Q_{FM}^{1.0774} \qquad (4.5)$$

Where Q_{MIX2} is the actual flow in this case and Q_{FM} is the flowmter reading.

4.1.6 Actual Flow

The actual flows of the aqueous solvent in this work are directly proportional with the flowmeter reading. The calibration of the flowmeter is crucial in order to maintain the consistency and accuracy of the experiment. The flowmeter is calibrated in water for the Typical Experiment. All the solvent flow in the experiment is converted to the actual reading by making use the obtained correlation as per shown in previous section.

4.2 RATE OF CO_2 ABSORPTION EXPERIMENT.

Rate of absorption of CO_2 into amine was determined from the gas phase material balance using the measured inlet and outlet gas concentration. On top of that the temperature readings were taken at the specific points on the wall of the Wetted Wall Column throughout the experiment at 1 minute interval. The temperature pattern of the column indicated the degree of reaction process (exothermic process) taking place in the column.

4.2.1 Effect of the Amine Concentration to the CO_2 Absorption Process

The study is very important as a preliminary medium to relate between the theoretical study and the industrial practices. The key points in this study are a main driver in order to achieve the goal and the target. As a starting point in this work is to understand the process and operational variables in the industry. The understanding is very important in order to ensure the scope of study is co-currently with the industrial practices.

Prior to the experiment, all of the modified apparatus and set up had been checked and calibrated. The corrected value of the solvent is required to analyze the experimental data at the later stage. From this work, all the flow factor of each of the solvent mixture was obtained. The calibration was carried out by making use of the volumetric cylinder as the calibration tank.

The absorption process of CO_2 into amine based solvent is an exothermic reaction, thus heat would be released during the experiment. Throughout the experiment, the temperature profiles on the column's wall were taken. The room temperature during the experiment was approximately 25 ^{o}C. It is essential to maintain the feed gas temperature at room temperature along the experiment to maintain the integrity of the experiment. The absorption process favors low temperature. The lower the temperature, the better the process. Inconsistency of the feed temperature would affect the entire experiment.

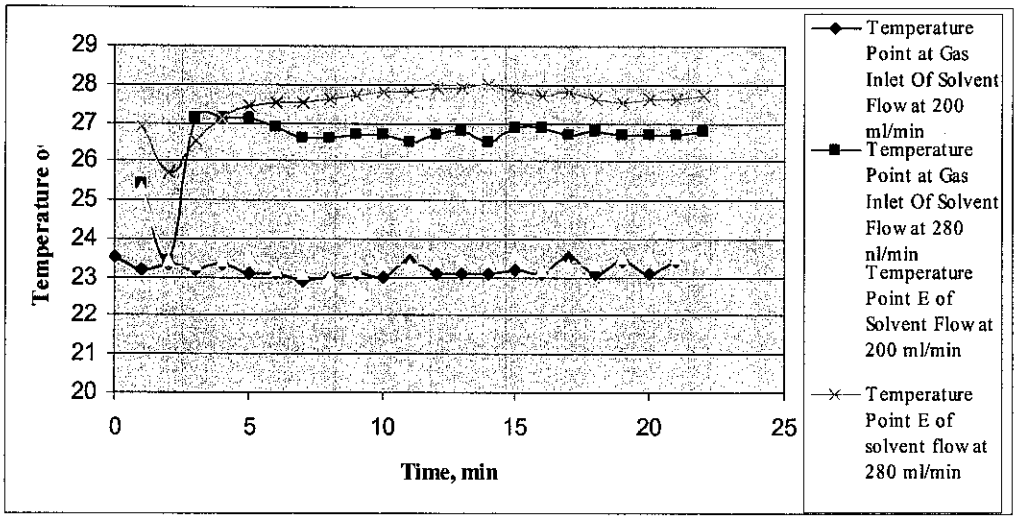

FIGURE 4.6: Temperature profile of experiment with 29.6 wt % DEA

The temperature at the feed of the column tends to drop over time due to the pressure differential across the gas regulator. This problem was minimized by installing the heat exchanger at the upstream of this feed gas line

From the experimental data, the CO_2 gas content at the outlet was reduced extremely at the initial stage of the experiment as well as the wall temperature. This indicates that the absorption process occur relatively higher at this point of time. These phenomenon arise at all of the experiments. Each of the experiment required different period to be in steady state condition. The longer the time taken, the slower the solvent react to the CO_2.

Obviously temperature rise tremendously at the initial process of the experiment. Slight drop of temperature during introducing gas to the apparatus is due to the low gas temperature. Higher temperature difference at the initial stage of the experiment shows that higher rate of absorption process at that point of time. This statement corresponds to the measured CO_2 at the outlet of the apparatus.

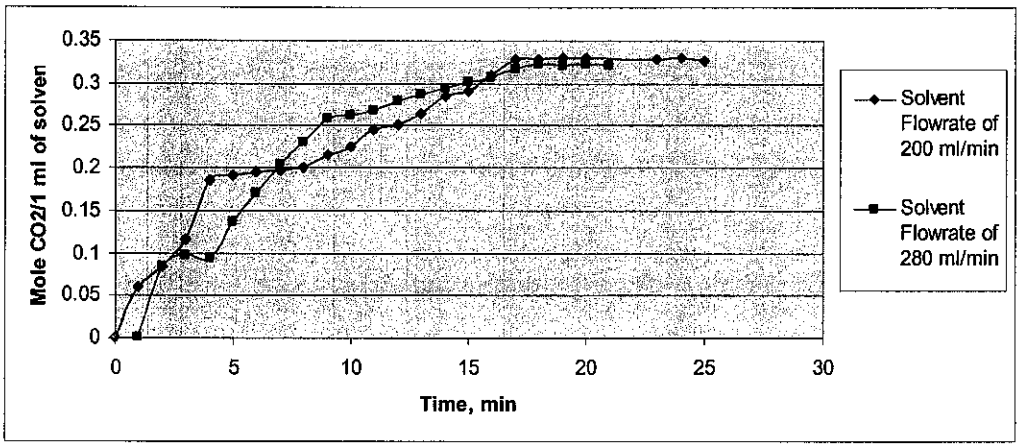

FIGURE 4.7: CO_2 loading profile over time for 29.6 wt% DEA.

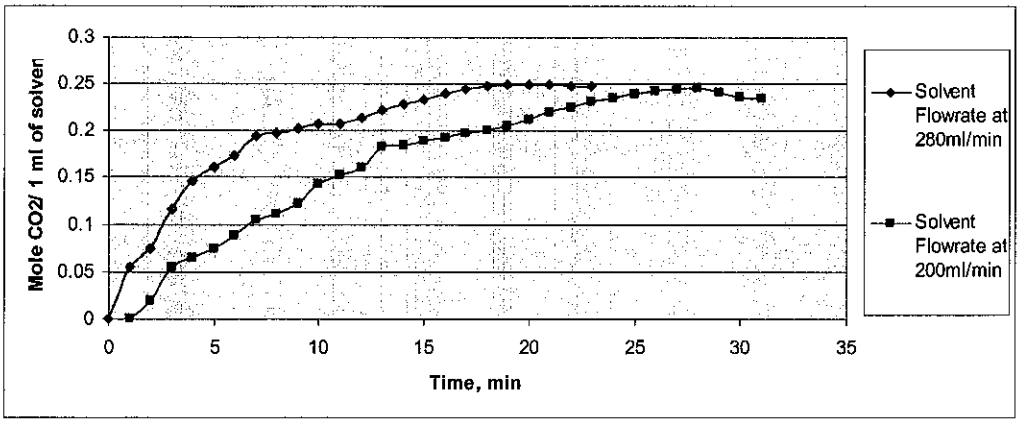

FIGURE 4.8: CO_2 loading profile over time for 26.7 wt% DEA.

The first experiment is to study the CO_2 absorption in the same amine at the different flowrate with similar concentration. Figure 4.7 and 4.8 show that the occurrence of the absorption process of CO_2 in DEA was at the tremendous rate. The absorption of CO_2 into amine is an exothermic reaction, thus heat would be released during the process. The temperatures of the wetted wall as well as some of the piping system were taken during the experiment. Only two points were taken in this analysis. The gas inlet temperature was taken due to the affect of temperature toward the absorption process. And the temperature at Point E was taken due to the observation during the experiment show that it is more sensitive to the change of the absorption process in this case. The gadget used to read the temperature was Carlsen IR Temperature Probe. Figure 4.6 and 4.9 show the temperature profile along the experiment.

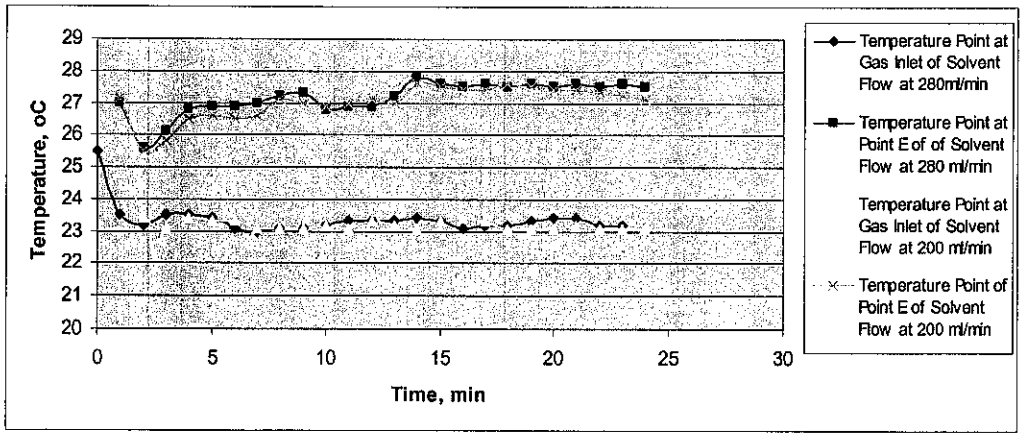

FIGURE 4.9: Temperature profile of experiment with 26.7 wt % DEA

Figure 4.7 and 4.8 show the relationship of using difference solvent flowrate with similar concentration. Obviously, the rate of absorption is faster at higher flowrate for both cases. The higher flowrate solvent will reach the equilibrium earlier. This can be seen in Figure 4.8, where higher flow 26.7 wt% solvent with 280 ml/min flowrate achieved the equilibrium earlier. However, the amount of CO_2 per volume of solvent is almost similar for the experiment with similar concentration.

4.2.2 Comparison of DEA with Various Concentrations at similar flowrate.

In this work, the comparison of concentration of amine in the solvent is one of the key points to figure out the relationship of that concentration and effectiveness of using those amines in CO_2 absorption. Figure 4.10 show the result of using similar amine with difference concentration at similar flowrate.

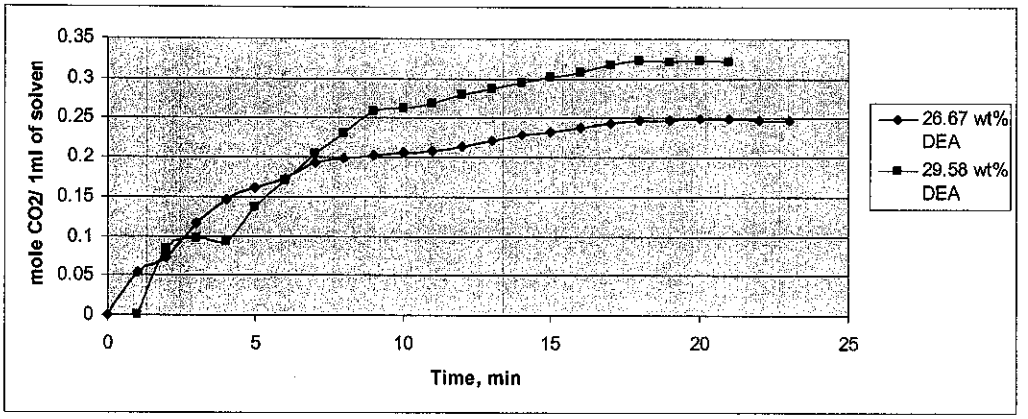

FIGURE 4.10: CO_2 loading profile over time for 26.7 wt% and 29.6 wt%DEA and at the flowrate or 280 ml/min.

Figure 4.14 show clearly that higher concentration of DEA would absorb more CO_2 relatively to the lower concentration of solvent in solvent. The rate of reaction was observed to be faster in higher concentration of DEA in the solvent as well.

In this case, 29.58 wt% DEA absorb approximately 0.34 mol CO_2 for every ml of solvent and only about 0.25 for 26.69 wt% DEA. The study of concentration effectiveness of this amine should be extended to some other value in order to obtain the optimum concentration of DEA. As per discussed in Chapter 2, the amount of CO_2 in the feedgas will affect the load of the unit, especially on the solvent.

The optimum concentration of this amine in the solvent is very crucial in order to maintain the smooth operation of the unit. Lower concentration of amine in the solvent might induce 'foaming' in the absorber column. This phenomenon will be elaborated more in the next section. Higher amount of amine in the solvent on the other will cost more in operating the unit.

It could be concluded that the solvent with similar flowrate at the difference concentration exhibits almost similar rate of reaction with CO_2 and difference in CO_2 loading capability.

4.2.3 Comparison of DEA and Mixture of MEA and DEA with Various Concentrations at Similar Flowrate.

Again this study is comparing the capability of each of the amine used in this work in term of concentration. In this section, the mixture of amine would be used as well. Theoretically, mixture of amine will perform better relatively to the single amine only. The comparison is also based on the concentration of each amine in the mixture as well as the single solvent. In order to maintain the consistency of the result of the experiment, the flowrate of the solvent were fixed at 280 ml/min.

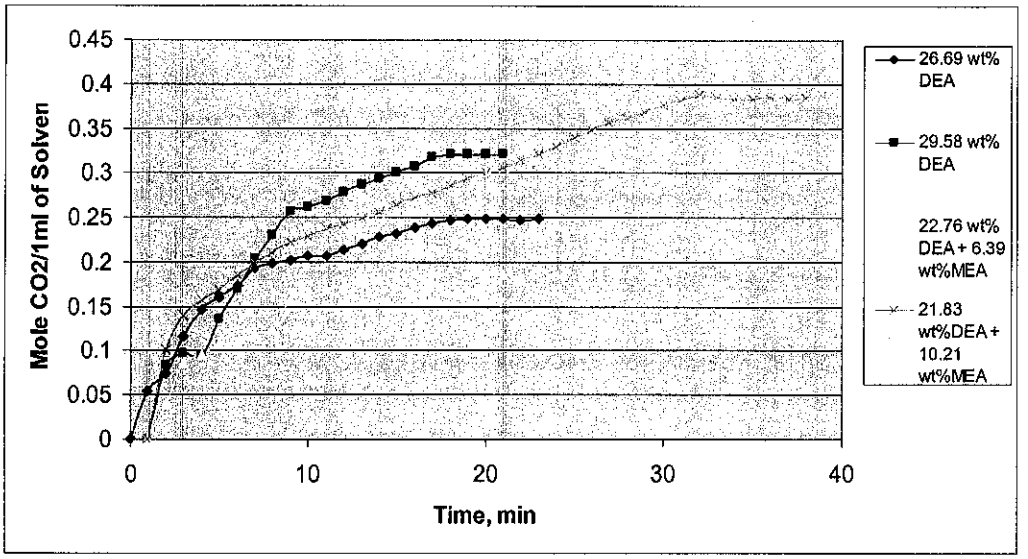

FIGURE 4.11: CO_2 loading of different Amine and Mixture with 280 ml/min of Solvent Flowrate over time.

Figure 4.15 shows that 26.69 wt% DEA in the amine solvent react faster relatively to the rest of the solvents. However the CO_2 loading of this solvent is no better than the mixture of solvent at 21.83 wt% DEA and 10.21 wt% MEA. This obtained result corresponds to the literature review in the Chapter 2. The mixture of solvent at the lower DEA exhibits less attractive result.

Obviously from the Figure 4.11, the mixture of 21.83 wt% DEA and 10.21 wt% MEA is able to absorb CO_2 at 0.38 moles per liter of solvent. By using this type of solvent, the operating cost relatively lower to any concentration or solvent used in

this work. However, more time needed before it able to achieve the steady state condition if compared to the solvent with 26.69 wt% DEA.

For all of the experiments in this work, the equilibrium state is assumed at the time of no decreasing in the CO_2 outlet concentration. The experiment would be considered complete at this point of time. This explains the lengths of some of the curve are not equal. On top of that the reaction rate would be measured from the length of this curve.

From this experiment can be concluded that the mixture of amine at 21.83 wt% DEA and 10.21 wt% MEA exhibits the most attractive amine to be used at higher concentration of CO_2 in the feedgas. However, this mixture would require higher Absorption column to react faster. The 'foaming' tendency of this mixture again will be compared to the other solvent in this work.

4.3 FOAMING TENDENCY TEST

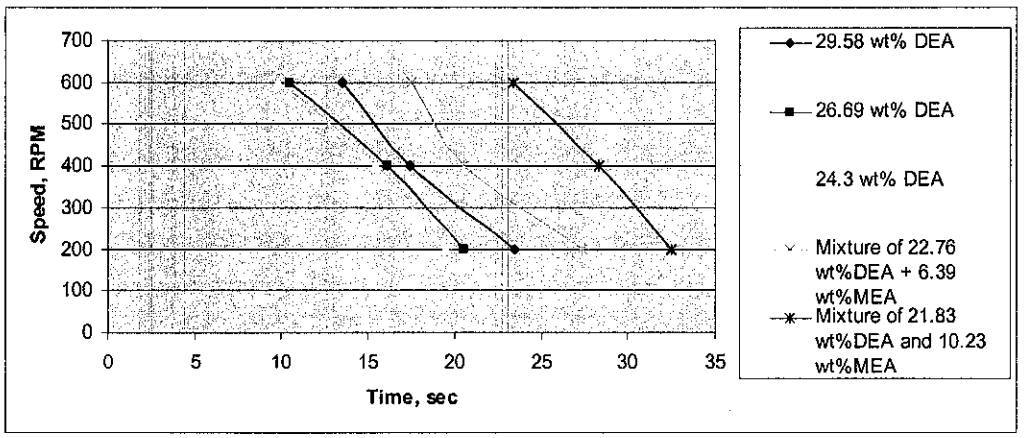

FIGURE 4.12: The foaming tendency profile Lean Solvent

The last set of experiment was to test the tendency of the solvent mixture to "Foaming". The worse condition was observed on the contaminated and fat solvent which is shown in figure 4.13 and 4.14. The amount of contaminant in the 1000 ml beaker is approximately 5 mg of sand.

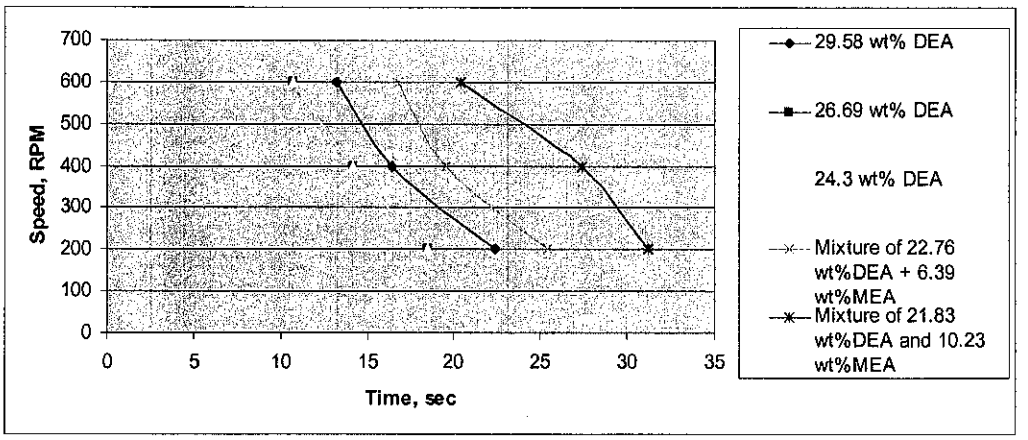

FIGURE 4.13: The foaming tendency profile Fat Solvent

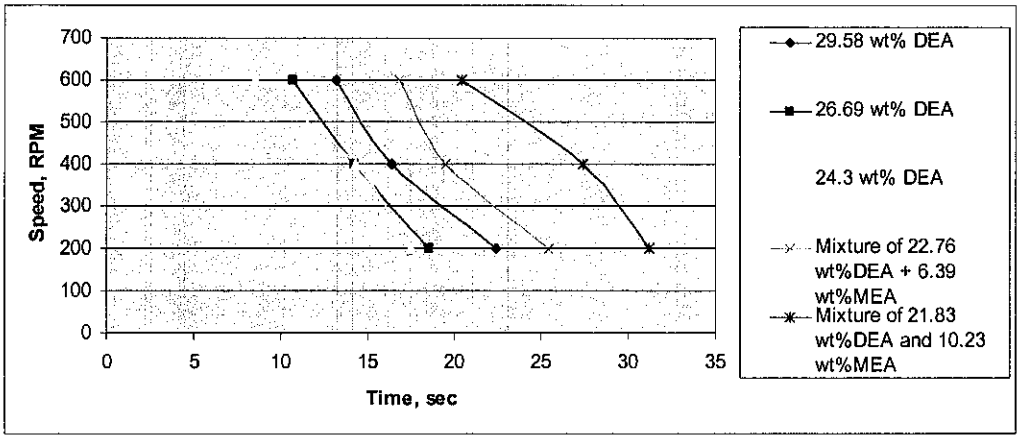

FIGURE 4.14: The foaming tendency profile Contaminated Solvent

Foaming was induced by disturb the mixture in the volumetric beaker. The higher speed of the stirrer will result in shorter time needed to foaming. Foaming is extremely dangerous to that particular unit operation and the environment. It might cause the equipment damage and loss of production time. If the problem was identified upfront, the hazards might be reduced.

Figure 4.16 shows the correlation between the concentration of amine in the solvent and the time taken to foaming. In this work, the single and less concentration of MEA was found to be most vulnerable solvent. It starts to foaming at the very fast rate as early as 10 seconds. The mixture of 21.83 wt% MEA and 10.23 wt% DEA was found to be the toughest solvent in this case.

Rate of foaming in the solvent is affected by various factors. One of the most important factors is water concentration in the solvent. The higher the water content, the higher the tendency of foaming in that particular solvent.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The equilibrium partial pressure of acid gases are above the amines define pinch condition for the absorber and stripper. Thermodynamics of aqueous amines are crucial to understand their industrial use to remove acid gases from the process stream. An understanding of this is important since the reactions are usually rate controlling. Furthermore, a consistent thermodynamics model can quantify the energy required for regenerating the solvent and solvent loses due to the amine volatility.

The flow meter used in this work was originally calibrated in water. Accurate measurement of the lean solvent flow at any particular time during the experiment is crucial in order to obtain the relationship between the Lean solvent flow and the gas flow. The flow of the solvent is one of the important elements in finding the most suitable for that particular process. The selection of this amine is mostly influenced by the load in the unit. Load of the unit is basically the amount of CO_2 to be removed from the stream.

Rate of absorption of CO_2 into amine was determined from the gas phase material balance using the measured inlet and outlet gas concentration. On top of that the temperature readings were taken at the specific points on the wall of the Wetted Wall Column throughout the experiment at 1 minute interval. The temperature pattern of the column indicated the degree of reaction process (exothermic process) taking place in the column. The higher the temperature detected, the higher the rate of reaction at that particular point. The temperatures at any points were changing tremendously at the initial part of the experiment. This indicates that the absorption

is occured the most at this point of time. This statement corresponds to the measured CO_2 at the outlet of the apparatus. The outlet concentration of CO_2 dropped tremendously at this time as well. This phenomenon might be affected by the temperature of the column as well as the solvent. The inlet and column temperature are very low at the initial start of the experiment. Theoretically, the absorption process favors low temperature.

From this experiment can be concluded that the mixture of amine at 21.83 wt% MEA and 10.21 wt% DEA exhibits the most attractive amine to be used at higher concentration of CO_2 in the feedgas. However, this mixture would require higher absorption column to react faster. The 'foaming' tendency of this mixture again will be compared to the other solvent in this work.

Rate of foaming in the solvent is affected by various factors. One of the most important factors is water concentration in the solvent. The higher the water content, the higher the tendency of foaming in that particular solvent. The mixture of 21.83 wt% MEA and 10.23 wt% DEA was found to be the toughest solvent in this case.

The mixture of 21.83 wt% MEA and 10.23 wt% DEA can be concluded as the most attractive solvent in this work in term of capability to absorb CO_2 as well as the resistance to faming. However, it won't be enough to justify that this solvent can be used to replace the existing solvent in the industry such as a-MDEA. More study on this solvent is required especially on the corrosiveness, hydrocarbon loading and reclamation process.

5.2 RECOMMENDATION

The improvement on the experimental apparatus would be the most critical issue on this study. The apparatus in this work was very vulnerable. The flow of gas was closely monitored at all the time during the experiment. One unit of stainless steel wetted wall column should be used in this research in order to obtain more accurate datas out of the experiments. During the experiment, some of the apparatus were not working properly and even not working at all. It is very important to ensure all the apparatus to be available all the time especially on the short project like this research.

The other issue during this work is the safety of the peoples around the apparatus. The plunge bath is not available in the lab. The shower and the eyes washer are not really testable. It might be very hard to clean or rinse the amine from any personnel in the event of emergency. The reliability of the safety equipment is not in good position. The usage of Personnel Protective Equipment (PPE) should be enforced to the personnel who are in the dangerous perimeter. Again, type of the PPE depends on the nature of that hazard and work.

One of the most critical issues in carrying out this experiment was the availability of the material. The material was delivered to the site at almost the end of the semester. Some of the materials were not delivered due to some constraints. The material should be available as early as the beginning of the semester. Nitrogen one of the affecting factors in this work. This research requires a very huge amount of Nitrogen. The nitrogen should be generated on site instead of purchasing it from the manufacturer. Most of the equipments in the lab need N_2 as an inert gas. Purchasing a small unit of N_2 generator won't be wastage in this case.

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APPENDICES

APPENDIX A-1: Experimental Data of CO_2 absorption in 26.69 wt% DEA at 200ml/min

t/min	CO2 vol%	Inlet T	A	B	C	D	E	F	G	H	Tank
0	16.22	25.6	23.1	25.3	27.3	27.2	27.1	26.5	27.1	26.3	26.6
1	15.5	23.4	23.2	23.9	24.3	22.3	25.5	25.5	24.5	24.5	26.3
2	14.2	23.1	23.1	24.5	24.6	21.9	25.8	25.9	25.9	25.1	25.9
3	13.8	23.4	23.1	25.6	25.6	21.3	26.5	26.5	26.4	25.9	25.8
4	13.45	23.3	23.2	25.5	25.7	21.9	26.6	26.9	26.8	26.1	26
5	12.94	23.3	23.1	25.6	25.7	21.8	26.5	27	26.8	26.2	25.9
6	12.31	23.1	23.2	25.7	25.7	21.9	26.6	26.8	26.8	26	26.1
7	12.1	23.1	23.2	25.6	25.7	21.9	27.1	26.8	26.9	25.9	26
8	11.7	23.1	23.1	25.6	25.8	22.1	27	26.9	27.4	26.3	26.3
9	10.9	23.2	23.1	25.5	25.7	22	26.9	26.8	27.2	26.4	26.2
10	10.55	23.1	23.1	25.2	25.5	22.1	27	26.9	26.8	26.3	26.3
11	10.23	23.3	23.2	25.1	25.5	22.4	27.1	27	27.1	26.5	26.4
12	9.41	23.2	23.1	25.2	25.4	22.3	27	26.8	26.9	26.5	26.3
13	9.33	23.1	23.2	25.1	25.4	22.3	27.6	26.7	27.1	26.4	26.3
14	9.15	23.3	23.1	25.1	25.5	22.3	27.5	26.4	27.2	26.4	26.1
15	9.05	23.4	23.1	25.1	25.4	22.2	27.4	26.4	26.9	26.5	26.3
16	8.84	23.3	23.3	25	25.5	22.3	27.4	26.4	26.8	26.4	26.4
17	8.75	23.1	23.2	24.7	25.4	22.2	27.6	26.5	26.5	26.5	26.3
18	8.55	23.1	23.2	24.3	25.3	22.3	27.5	26.5	26.6	26.5	26.1
19	8.31	23.1	23.3	24.3	25.2	22.2	27.4	26.6	26.6	26.7	26.1
20	8.05	23.2	23.1	24.3	25.1	22.2	27.4	26.4	26.5	26.5	26.2
21	7.85	23.1	23.1	24.4	25.2	22.1	27.3	26.5	26.6	26.5	26
22	7.64	23.1	23.1	24.3	25.2	22.2	27.2	26.4	26.3	26.3	26.1
23	7.51	23.1	23.2	24.3	25.1	22.2	27.1	25.9	25.8	25.6	25.9
24	7.34	23.2	23.1	24.2	25.2	22.1	27.1	26.1	25.7	25.9	25.8
25	7.2	23.1	23.2	24.2	25.1	22.2	27.1	25.8	25.7	25.7	26.5
26	7.15	23.2	23.2	24.1	25.1	22.1	26.8	25.7	25.7	25.6	26.1
27	7.08	23.2	23.1	23.8	25.2	22.2	26.3	25.9	25.4	25.6	25.9
28	7.24	23.1	23.1	23.9	25.1	22.1	26.8	25.8	25.7	25.7	26.4
29	7.45	23.2	23.1	23.7	25.1	22.2	26.7	25.8	25.9	26	26.3
30	7.5	23.2	23.2	23.8	25.1	22.1	27	25.9	25.8	25.8	26.3

APPENDIX A-2: Calculated Data of calculated absorbed CO_2 in 26.69 wt% DEA at 200ml/min

CO2 Flowrate = 2150 ml/min

CO2 mass flowrate = [redacted] kg/min

CO2 mole flowrate = 87.05521472 mole/min

DEA 27 wt%
Flowrate: 200 cc/min

t/min	CO2 vol%	mole/min	Ref CO2 vol%	Outlet CO2 mole/min	Absorbed CO2, mole/min	Mole CO2/ 1 ml of amine
0	16.22	87.05	16.22	87.05	0	0
1	15.5	87.05	16.22	83.18588163	3.864118372	0.019320592
2	14.2	87.05	16.22	76.20900123	10.84099877	0.054204994
3	13.8	87.05	16.22	74.0622688	12.9877312	0.064938656
4	13.45	87.05	16.22	72.18387793	14.86612207	0.07433061
5	12.94	87.05	16.22	69.44679408	17.60320592	0.08801603
6	12.31	87.05	16.22	66.06569051	20.98430949	0.104921547
7	12.1	87.05	16.22	64.93865598	22.11134402	0.11055672
8	11.7	87.05	16.22	62.79192355	24.25807645	0.121290382
9	10.9	87.05	16.22	58.49845869	28.55154131	0.142757707
10	10.55	87.05	16.22	56.62006782	30.42993218	0.152149661
11	10.23	87.05	16.22	54.90268187	32.14731813	0.160736591
12	9.41	87.05	16.22	50.50188039	36.54811961	0.182740598
13	9.33	87.05	16.22	50.07253391	36.97746609	0.18488733
14	9.15	87.05	16.22	49.10650432	37.94349568	0.189717478
15	9.05	87.05	16.22	48.56982121	38.48017879	0.192400894
16	8.84	87.05	16.22	47.44278668	39.60721332	0.198036067
17	8.75	87.05	16.22	46.95977189	40.09022811	0.200451141
18	8.55	87.05	16.22	45.88640567	41.16359433	0.205817972
19	8.31	87.05	16.22	44.59836621	42.45163379	0.212258169
20	8.05	87.05	16.22	43.20299014	43.84700986	0.219235049
21	7.85	87.05	16.22	42.12962392	44.92037608	0.22460188
22	7.64	87.05	16.22	41.0025894	46.0474106	0.230237053
23	7.51	87.05	16.22	40.30490136	46.74509864	0.233725493
24	7.34	87.05	16.22	39.39254007	47.65745993	0.2382873
25	7.2	87.05	16.22	38.64118372	48.40881628	0.242044081
26	7.15	87.05	16.22	38.37284217	48.67715783	0.243385789
27	7.08	87.05	16.22	37.997164	49.052836	0.24526418
28	7.24	87.05	16.22	38.85585697	48.19414303	0.240970715
29	7.45	87.05	16.22	39.98289149	47.06710851	0.235335543
30	7.5	87.05	16.22	40.25123305	46.79876695	0.233993835

APPENDIX A-3: Experimental Data of CO_2 absorption in 26.69 wt% DEA at 280ml/min

t/min	CO2 vol%	Inlet T	A	B	C	D	E	F	G	H	Tank
0	16.5	25.5	23.1	25.2	27.1	27.1	27	26.3	27	26.2	26.5
1	13.7	23.5	23.6	24.5	24.5	22.5	25.6	25.6	25.5	24.5	26.4
2	12.7	23.2	23.3	25	25	22	26.1	26.1	26	25.1	26.2
3	10.5	23.5	23.2	25.7	25.7	21.4	26.8	26.8	26.8	26	26.2
4	8.95	23.5	23.1	25.8	25.8	22.1	26.9	26.9	26.9	26.4	26.1
5	8.2	23.4	23.2	25.7	25.8	22.1	26.9	27	26.8	26.3	26.1
6	7.55	23.1	23.1	25.6	25.9	22.2	27	27	27	26.2	26.3
7	6.46	23	23.1	25.4	25.8	22.1	27.2	26.8	27.1	26.3	26.3
8	6.25	23.1	23.1	25.3	25.6	22.1	27.3	27.2	27.4	26.3	26.3
9	6.05	23.1	23.1	25.2	25.5	22	26.8	29.7	26.9	26.4	26.4
10	5.8	23.2	23.2	25.2	25.5	22.3	26.9	26.9	26.9	26.2	26.3
11	5.75	23.3	23.1	25.3	25.6	22.5	26.9	26.8	26.9	26.4	26.2
12	5.45	23.3	23.3	25.1	25.5	22.4	27.2	26.7	27.1	26.5	26.6
13	5.05	23.3	23.1	25.2	25.3	22.3	27.8	26.6	27.2	26.5	26.6
14	4.65	23.4	23.2	25.2	25.4	22.1	27.6	26.4	26.9	26.5	26.5
15	4.45	23.3	23.2	25.2	25.4	22.3	27.5	26.5	26.8	26.4	26.6
16	4.13	23.1	23.2	24.9	25.2	22.4	27.6	26.5	26.7	26.5	26.5
17	3.87	23.2	23.1	24.8	25.3	22.3	27.5	26.6	26.7	26.4	26.4
18	3.7	23.2	23.4	24.4	25.4	22.3	27.6	26.6	26.7	26.6	26.4
19	3.64	23.3	23.4	24.4	25.3	22.3	27.5	26.8	26.7	26.5	26.5
20	3.57	23.4	23.3	24.5	25.2	22.1	27.6	26.7	26.6	26.5	26.3
21	3.63	23.4	23.2	24.4	25.1	22.1	27.5	26.4	26.4	26.3	26.2
22	3.7	23.2	23.2	24.4	25.1	22.1	27.6	26.3	26.4	26.3	26.2
23	3.65	23.2	23.1	24.3	25.3	22.1	27.5	26.1	26.3	26.3	26.1

APPENDIX A-4: Calculated Data of calculated absorbed CO_2 in 26.69 wt% DEA at 280ml/min

CO2 Flowrate = 2200

CO2 mass flowrate = 3.9204 kg/min

CO2 mole flowrate = 89.0797546 mole/min

DEA 27 wt%
Flowrate: 280 cc/min

t/min	CO2 vol%	mole/min	Ref CO2 vol%	Outlet CO2 mole/min	Absorbed CO2, mole/min	Mole CO2/ 1 ml of amine
0	16.5	89.08	16.5	89.08	0	0
1	13.7	89.08	16.5	73.96339394	15.11660606	0.053987879
2	12.7	89.08	16.5	68.56460606	20.51539394	0.073269264
3	10.5	89.08	16.5	56.68727273	32.39272727	0.115688312
4	8.95	89.08	16.5	48.31915152	40.76084848	0.145574459
5	8.2	89.08	16.5	44.27006061	44.80993939	0.160035498
6	7.55	89.08	16.5	40.76084848	48.31915152	0.172568398
7	6.46	89.08	16.5	34.8761697	54.2038303	0.193585108
8	6.25	89.08	16.5	33.74242424	55.33757576	0.197634199
9	6.05	89.08	16.5	32.66266667	56.41733333	0.201490476
10	5.8	89.08	16.5	31.3129697	57.7670303	0.206310823
11	5.75	89.08	16.5	31.0430303	58.0369697	0.207274892
12	5.45	89.08	16.5	29.42339394	59.65660606	0.213059307
13	5.05	89.08	16.5	27.26387879	61.81612121	0.220771861
14	4.65	89.08	16.5	25.10436364	63.97563636	0.228484416
15	4.45	89.08	16.5	24.02460606	65.05539394	0.232340693
16	4.13	89.08	16.5	22.29699394	66.78300606	0.238510736
17	3.87	89.08	16.5	20.89330909	68.18669091	0.243523896
18	3.7	89.08	16.5	19.97551515	69.10448485	0.246801732
19	3.64	89.08	16.5	19.65158788	69.42841212	0.247958615
20	3.57	89.08	16.5	19.27367273	69.80632727	0.249308312
21	3.63	89.08	16.5	19.5976	69.4824	0.248151429
22	3.7	89.08	16.5	19.97551515	69.10448485	0.246801732
23	3.65	89.08	16.5	19.70557576	69.37442424	0.247765801

APPENDIX A-5: Experimental Data of CO_2 absorption in 29.6 wt% DEA at 200ml/min

t/min	CO2 vol%	Inlet T	A	B	C	D	E	F	G	H	Tank
0	10.1	25.3	23	25.1	27.1	27	26.9	26.1	26.9	26	26.5
1	8.9	23.4	23.6	24.5	24.4	22.2	25.7	25.7	25.6	24.6	26.3
2	8.43	23.3	23.4	25.2	25.2	22.1	26.5	26.4	26.4	25.4	26.3
3	7.78	23.4	23.3	25.9	25.9	21.5	27.1	27.1	27	26.1	26.3
4	6.41	23.5	23.2	25.6	26.1	22.1	27.4	27.3	26.9	26.5	26.2
5	6.3	23.2	23.1	25.6	26.1	22.2	27.5	26.9	27	26.4	26.3
6	6.21	23.1	23	25.5	26.1	22.3	27.5	26.8	27.1	26.4	26.3
7	6.19	23	23	25.3	25.8	22.2	27.6	26.5	27.1	26.4	26.4
8	6.09	23.2	23	25.3	25.8	22.1	27.7	26.9	26.8	26.5	26.4
9	5.8	23.3	23.1	25.2	25.6	22.1	27.8	26.9	26.8	26.3	26.4
10	5.63	23.3	23.2	25.2	25.7	22.4	27.8	26.7	26.8	26.3	26.4
11	5.22	23.4	23.2	25.1	25.6	22.5	27.9	26.8	26.9	26.6	26.5
12	5.1	23.5	23.1	25.2	25.8	22.5	27.9	26.8	27.1	26.4	26.5
13	4.83	23.4	23.1	25.2	25.4	22.5	28	26.6	27.1	26.4	26.3
14	4.42	23.6	23.3	25.3	25.7	22.3	27.8	26.6	27.3	26.6	26.3
15	4.3	23.2	23.4	25.3	25.3	22.5	27.7	26.6	26.9	26.5	26.4
16	3.92	23.3	23.3	24.9	25.3	22.5	27.8	26.7	26.8	26.3	26.4
17	3.57	23.3	23.2	24.6	25.5	22.4	27.6	26.7	26.8	26.4	26.3
18	3.55	23.5	23.5	24.4	25.4	22.3	27.5	26.5	26.6	26.5	26.3
19	3.53	23.6	23.5	24.5	25.4	22.2	27.6	26.5	26.5	26.5	26.2
20	3.54	23.5	23.4	24.5	25.2	22.2	27.6	26.3	26.5	26.5	26.1
21	3.56	23.5	23.3	24.4	25.1	22.2	27.7	26.4	26.5	26.5	26.1
22	3.54	23.2	23.4	24.5	25.2	22.3	27.6	26.4	26.5	26.5	26.1
23	3.55	23.4	23.3	24.4	25.2	22.2	27.6	26.4	26.4	26.4	26.2
24	3.54	23.4	23.4	24.5	25.2	22.4	27.7	26.4	26.5	26.5	26.1
25	3.6	23.2	23.3	24.4	25.2	22.3	27.7	26.5	26.4	26.4	26.2

APPENDIX A-6: Calculated Data of calculated absorbed CO_2 in 29.6 wt% DEA at 200ml/min

CO2 Flowrate = 2500 ml/min

CO2 mass flowrate = 4.455 kg/min

CO2 mole flowrate = 101.227 mole/min

DEA 29.58 wt%
Flowrate: 200 cc/min

t/min	CO2 vol%	mole/min	Ref CO2 vol%	Outlet CO2 mole/min	Absorbed CO2, mole/min	Mole CO2/ 1 ml of amine
0	10.1	101.2	10.1	101.2	0	0
1	8.9	101.2	10.1	89.17623762	12.02376238	0.060118812
2	8.43	101.2	10.1	84.46693069	16.73306931	0.083665347
3	7.78	101.2	10.1	77.95405941	23.24594059	0.116229703
4	6.41	101.2	10.1	64.22693069	36.97306931	0.184865347
5	6.3	101.2	10.1	63.12475248	38.07524752	0.190376238
6	6.21	101.2	10.1	62.2229703	38.9770297	0.194885149
7	6.19	101.2	10.1	62.02257426	39.17742574	0.195887129
8	6.09	101.2	10.1	61.02059406	40.17940594	0.20089703
9	5.8	101.2	10.1	58.11485149	43.08514851	0.215425743
10	5.63	101.2	10.1	56.41148515	44.78851485	0.223942574
11	5.22	101.2	10.1	52.30336634	48.89663366	0.244483168
12	5.1	101.2	10.1	51.1009901	50.0990099	0.25049505
13	4.83	101.2	10.1	48.39564356	52.80435644	0.264021782
14	4.42	101.2	10.1	44.28752475	56.91247525	0.284562376
15	4.3	101.2	10.1	43.08514851	58.11485149	0.290574257
16	3.92	101.2	10.1	39.27762376	61.92237624	0.309611881
17	3.57	101.2	10.1	35.77069307	65.42930693	0.327146535
18	3.55	101.2	10.1	35.57029703	65.62970297	0.328148515
19	3.53	101.2	10.1	35.36990099	65.83009901	0.329150495
20	3.54	101.2	10.1	35.47009901	65.72990099	0.328649505
23	3.55	101.2	10.1	35.57029703	65.62970297	0.328148515
24	3.54	101.2	10.1	35.47009901	65.72990099	0.328649505
25	3.6	101.2	10.1	36.07128713	65.12871287	0.325643564

APPENDIX A-7: Experimental Data of CO2 absorption in 29.6 wt% DEA at 280 ml/min

time/min	CO2 vol%	Gas inlet	A	B	C	D	E	F	G	H	Solvent T	Tank
0	5.67	23.5	21.6	22.6	22.5	22.4	22.9	23.2	23.1	23.9	24	26.4
1	4.21	23.2	22.5	25.3	25.6	22.1	26.6	26.6	27	25.8	25.5	26.5
2	3.98	23.3	22.8	25.9	25.9	22.3	27.1	27.1	26.7	25.9	25.5	26.5
3	4.03	23.2	23.2	26.1	26.1	22.5	27.1	27.1	27.1	26.3	26.3	26.3
4	3.3	23.3	23.5	26	24.9	22	27.1	27.1	27.1	26.4	26.1	26
5	2.7	23.1	23.6	25.8	25.8	21.8	26.9	26.9	27	26.4	25.9	26.1
6	2.13	23.1	23.7	25.8	25.8	21.9	26.6	26.7	26.8	26.4	26.4	26.1
7	1.66	22.9	23.6	25.7	25.8	21.6	26.6	26.7	26.8	26.1	26.4	25.9
8	1.18	23	23.6	25.4	25.7	21.6	26.7	26.7	26.8	26.4	25.9	26.1
9	1.1	23.1	23.6	25.3	25.6	22.4	26.7	26.7	26.8	26.4	26.3	26
10	1	23	23.6	25.3	25.4	21.1	26.5	26.6	26.8	26.4	25.7	25.9
11	0.8	23.4	23.4	25.6	25.9	22.2	26.7	26.8	27.1	26.5	25.9	26
12	0.68	23.1	23.6	25.6	25.6	21.3	26.8	27	26.9	26.4	26.1	26.1
13	0.55	23.1	23.6	25.8	25.8	21.5	26.5	26.9	27.1	26.4	25.9	26.2
14	0.42	23.1	23.8	25.7	25.9	21.4	26.9	27	27.1	26.6	26.2	26.2
15	0.31	23.2	23.8	25.7	25.8	21.9	26.9	27.1	27.1	26.6	26.3	26.1
16	0.15	23.1	23.8	25.6	25.6	21.1	26.7	26.8	26.9	26.4	25.5	26.1
17	0.07	23.5	23.8	25.8	25.8	21.3	26.8	26.8	27	26.5	26.1	26.1
18	0.08	23.1	23.7	25.6	25.6	21.1	26.7	26.8	26.9	26.5	25.5	26.3
19	0.07	23.4	23.8	25.8	25.6	21.1	26.7	26.8	27.1	26.4	25.9	26.2
20	0.09	23.1	23.8	25.8	25.6	21.1	26.7	26.8	26.9	26.5	25.4	26.2
21	0.08	23.4	23.7	25.8	25.4	21.3	26.8	26.7	27	26.4	25.8	26.3

APPENDIX A-8: Calculated Data of calculated absorbed CO_2 in 29.6 wt% DEA at 280ml/min

CO2 Flowrate = 2250 ml/min

CO2 mass flowrate = [illegible] kg/min

CO2 mole flowrate = 91.10429448 mole/min

Solvent: DEA
Flowrate: 280 cc/min

time/min	CO2 vol%	mole/min	Ref CO2 vol%	Outlet CO2 mole/min	Absorbed CO2, mole/min	Mole CO2/ 1 ml of amine
0	5.67	91.1	5.67	91.1	0	0
1	4.21	91.1	5.67	67.64215168	23.45784832	0.08377803
2	3.98	91.1	5.67	63.94673721	27.15326279	0.096975939
3	4.03	91.1	5.67	64.75008818	26.34991182	0.094106828
4	3.3	91.1	5.67	53.02116402	38.07883598	0.135995843
5	2.7	91.1	5.67	43.38095238	47.71904762	0.17042517
6	2.13	91.1	5.67	34.22275132	56.87724868	0.203133031
7	1.66	91.1	5.67	26.6712522	64.4287478	0.230102671
8	1.18	91.1	5.67	18.95908289	72.14091711	0.257646133
9	1.1	91.1	5.67	17.67372134	73.42627866	0.262236709
10	1	91.1	5.67	16.0670194	75.0329806	0.267974931
11	0.8	91.1	5.67	12.85361552	78.24638448	0.279451373
12	0.68	91.1	5.67	10.92557319	80.17442681	0.286337239
13	0.55	91.1	5.67	8.83686067	82.26313933	0.293796926
14	0.42	91.1	5.67	6.748148148	84.35185185	0.301256614
15	0.31	91.1	5.67	4.980776014	86.11922399	0.307568657
16	0.15	91.1	5.67	2.41005291	88.68994709	0.316749811
17	0.07	91.1	5.67	1.124691358	89.97530864	0.321340388
18	[illegible]	91.1	5.67	1.285361552	89.81463845	0.320766566
19	0.07	91.1	5.67	1.124691358	89.97530864	0.321340388
20	[illegible]	91.1	5.67	1.446031746	89.65396825	0.320192744

APPENDIX A-9: Experimental Data of CO_2 absorption in 22.76 wt% DEA and 6.39 wt% MEA at 280 ml/min

t/min	CO2 vol%	inlet T	A	B	C	D	E	F	G	H	Tank
0	14	22.7	20.4	21.1	20.4	20.4	21.2	21.2	22	23.5	26.8
1	12.74	22.9	21.3	23.2	23.6	20.4	26.1	26.1	26.2	24.1	27
2	11.36	23	22.1	26.6	26.6	20.4	27.6	27.6	27.4	25.6	26.9
3	11.08	23	22.6	27.4	27.4	20.6	28.3	28.2	27.8	26.3	26.1
4	10.71	22.8	23.6	27.8	27.8	20.8	28.6	28.5	27.9	26.6	26.1
5	10.64	23.1	24.3	28.2	28.1	21.1	28.8	28.4	28.3	26.9	26.9
6	10.36	22.9	24.5	28	27.9	21.4	28.8	28.9	28.1	27.1	26.9
7	10.18	23.1	24.9	28.1	28	21.6	28.8	28.6	28.3	27.1	26.9
8	9.15	23	24.9	28.1	27.8	21.5	28.8	28.6	28.6	27.4	27.1
9	9	23.2	24.9	28	27.9	21.4	28.6	28.6	28.4	27.3	27.1
10	8.79	23.9	25	27.9	27.9	21.1	28.7	28.4	28.4	27.5	26.9
11	8.68	23.1	25	27.8	27.8	21.3	28.9	28.9	28.7	27.6	27
12	8.55	23.1	24.9	27.8	27.8	21.4	28.6	28.7	28.6	27.3	27.1
13	8.43	23.1	24.9	27.8	27.9	21.3	29.1	28.6	28.6	27.4	27.2
14	8.3	22.9	24.9	27.8	27.6	21.9	28.7	28.3	28.4	27.6	27.1
15	8.21	23.1	24.8	27.7	27.7	22	28.6	28.6	28.3	27.4	27.1
16	8.13	23.1	24.5	27.7	27.7	21.8	28.6	28.3	28.3	27.4	27.1
17	8.06	23.1	24.7	27.6	27.6	21.9	28.6	28.6	28.2	27.3	27.1
18	8.25	22.9	24.5	27.6	27.5	21.4	28.3	28.4	28.2	27.4	27
19	8.3	23	24.5	27.6	27.5	21.6	28.5	28.5	28.3	27.4	27.1
20	8.27	23	24.6	27.4	27.5	21.4	28.3	28.4	28.4	27.1	27.3
21	8.35	23	24.5	27.6	27.4	21.6	28.3	28.4	28.4	27.1	27.3

APPENDIX A-10: Calculated Data of calculated absorbed CO_2 in 22.76 wt% DEA and 6.39 wt% MEA at 280 ml/min

CO2 Flowrate = 2250 ml/min

CO2 mass flowrate = [redacted] kg/min

CO2 mole flowrate = 91.10429448 mole/min

DEA 29.58 wt%
Flowrate: 200 cc/min

t/min	CO2 vol%	mole/min	Ref CO2 vol%	Outlet CO2 mole/min	Absorbed CO2, mole/min	Mole CO2/ 1 ml of amine
0	14	91.1	14	91.1	0	0
1	12.74	91.1	14	82.901	8.199	0.040995
2	11.36	91.1	14	73.92114286	17.17885714	0.085894286
3	11.08	91.1	14	72.09914286	19.00085714	0.095004286
4	10.71	91.1	14	69.6915	21.4085	0.1070425
5	10.64	91.1	14	69.236	21.864	0.10932
6	10.36	91.1	14	67.414	23.686	0.11843
7	10.18	91.1	14	66.24271429	24.85728571	0.124286429
8	9.15	91.1	14	59.54035714	31.55964286	0.157798214
9	9	91.1	14	58.56428571	32.53571429	0.162678571
10	8.79	91.1	14	57.19778571	33.90221429	0.169511071
11	8.68	91.1	14	56.482	34.618	0.17309
12	8.55	91.1	14	55.63607143	35.46392857	0.177319643
13	8.43	91.1	14	54.85521429	36.24478571	0.181223929
14	8.3	91.1	14	54.00928571	37.09071429	0.185453571
15	8.21	91.1	14	53.42364286	37.67635714	0.188381786
16	8.13	91.1	14	52.90307143	38.19692857	0.190984643
17	8.06	91.1	14	52.44757143	38.65242857	0.193262143
18	8.25	91.1	14	53.68392857	37.41607143	0.187080357
19	[redacted]	91.1	14	54.00928571	37.09071429	0.185453571
20	[redacted]	91.1	14	53.81407143	37.28592857	0.186429643
21	[redacted]	91.1	14	54.33464286	36.76535714	0.183826786

APPENDIX A-11: Experimental Data of CO_2 absorption in 21.83 wt% DEA and 10.23 wt% MEA at 280 ml/min

t/min	inlet T	CO2 vol%	A	B	C	D	E	F	G	H	Solvent	Tank
0	22.7	14.6	22.2	22.5	22.4	22.3	22.3	22.7	23.1	22.7	27.8	26.7
1	22.8	11.67	22.8	27.3	27.2	21.8	28.2	28.1	27.9	25.3	27.9	25.8
2	23	10.5	23.6	28.7	28.7	21.4	29.3	29.1	28.6	26.7	26.8	28
3	22.9	10.01	24.3	29.2	29.2	21.4	29.8	29.5	29.1	27.4	27.7	28.1
4	22.7	9.66	24.7	29.4	29.4	21.9	29.8	29.8	29.4	27.6	25.9	28.1
5	22.8	9.21	25.1	29.3	29.3	21.9	29.9	29.9	29.4	28.1	27.9	28.2
6	22.8	8.79	25.4	29.3	29.3	21.4	29.9	30	29.4	28.4	26.5	28.3
7	23	8.43	25.6	29.1	29.1	21.3	29.9	30	29.7	28.3	28.2	28.2
8	22.8	8.08	25.8	29.4	29.4	21.7	30	30	29.5	28.6	27.5	28.4
9	23	7.9	25.6	29.3	29.3	21.6	29.9	30	29.5	28.5	27.8	28.3
10	23.1	7.68	25.8	29.1	29.1	21.3	30.1	30.1	29.8	28.8	27.8	28.4
11	23	7.5	25.8	29.2	29.2	21.4	30	30.1	29.5	29.1	28.8	28.4
12	23.1	7.31	25.8	29.2	29.3	21.7	30.1	30	29.6	29	28.9	28.4
13	23.3	7.11	26	29.3	29.3	22	30.4	30.3	29.9	29.1	28.4	28.4
14	23.1	6.89	25.9	29.3	29.3	21.8	30.2	30.4	30	29.3	28.8	28.5
15	23.1	6.61	26	29.2	29.2	21.7	30.2	30.1	30.1	29.3	28.3	28.7
16	23.2	6.46	25.9	29.1	29.1	21.8	30.3	30.3	30.1	29.4	28.8	28.5
17	23.2	6.21	26	28.9	29	21.8	30.2	30.1	30.1	29.3	29.2	28.6
18	23.2	6.01	26	28.9	28.9	21.6	30.1	30.2	30	29.4	29.3	28.6
19	23.1	5.81	26	28.9	28.9	21.7	30.2	30.2	30	29.3	27.9	28.5
20	23.2	5.64	25.9	28.9	29	21.5	30.2	30.5	30	29.4	28.3	28.7
21	23.1	5.4	26.1	28.9	28.9	21.3	30.3	30.2	30	29.3	28.4	28.4
22	23.1	5.2	26.1	28.8	28.8	21.3	30.2	30	30	29.5	29.1	28.6
23	23.2	4.93	25.9	28.8	28.8	21.3	30	30	30.1	29.5	28.1	28.4
24	23.2	4.64	26.1	28.6	28.6	20.9	30	30.1	30.1	29.4	28.6	28.5
25	23.2	4.41	26.1	28.6	28.6	21.2	29.9	30	29.9	29.4	29.5	28.6
26	23.1	4.18	25.9	28.4	28.4	20.9	29.9	29.9	30	29.5	29.1	28.4
27	23.2	4.03	26	28.5	28.5	20.9	29.9	30	29.9	29.6	29.1	28.4
28	23.2	3.84	25.9	28.4	28.5	21.1	30.1	30	30	29.7	28.9	28.4
29	23.1	3.58	25.9	28.3	28.3	21.1	29.9	29.9	29.9	30.2	29.4	28.6
30	23.2	3.42	25.8	28.3	28.3	21	29.8	29.9	29.9	29.6	28.3	28.4
31	23.2	3.23	25.8	28.3	28.1	20.9	29.6	29.6	30	29.6	29.3	28.3
32	23.1	[illegible]	25.6	28.4	28.3	21.1	29.8	29.6	29.8	29.5	28.7	28.4
33	23.1	[illegible]	25.6	28.3	28.1	20.9	29.6	29.5	30	29.5	28.9	28.3
34	23.2	[illegible]	25.7	28.3	28.1	20.9	29.6	29.6	29.9	29.5	28.7	28.4
35	23.1	[illegible]	25.6	28.4	28.3	20.7	29.6	29.6	29.9	29.6	28.8	28.3
36	23.1	[illegible]	25.6	28.3	28.3	21.1	29.7	29.7	29.8	29.5	28.6	28.3
37	23.1	[illegible]	25.6	28.3	28.2	20.8	29.6	29.6	29.8	29.5	28.7	28.4

APPENDIX A-12: Calculated Data of calculated absorbed CO_2 in in 21.83 wt% DEA and 10.23 wt% MEA at 280 ml/min

CO2 Flowrate = 2460 ml/min

CO2 mass flowrate = 4.38372 kg/min

CO2 mole flowrate = 99.60736196 mole/min

MIX 2
Flowrate: 280 cc/min

t/min	CO2 vol%	mole/min	Ref CO2 vol%	Outlet CO2 mole/min	Absorbed CO2, mole/min	Mole CO2/ 1 ml of amine
0	14.6	99.61	14.6	99.61	0	0
1	11.67	99.61	14.6	79.61977397	19.99022603	0.09995113
2	10.5	99.61	14.6	71.63732877	27.97267123	0.139863356
3	10.01	99.61	14.6	68.29425342	31.31574658	0.156578733
4	9.66	99.61	14.6	65.90634247	33.70365753	0.168518288
5	9.21	99.61	14.6	62.83617123	36.77382877	0.183869144
6	8.79	99.61	14.6	59.97067808	39.63932192	0.19819661
7	8.43	99.61	14.6	57.5145411	42.0954589	0.210477295
8	8.08	99.61	14.6	55.12663014	44.48336986	0.222416849
9	7.9	99.61	14.6	53.89856164	45.71143836	0.228557192
10	7.68	99.61	14.6	52.39758904	47.21241096	0.236062055
11	7.5	99.61	14.6	51.16952055	48.44047945	0.242202397
12	7.31	99.61	14.6	49.87322603	49.73677397	0.24868387
13	7.11	99.61	14.6	48.50870548	51.10129452	0.255506473
14	6.89	99.61	14.6	47.00773288	52.60226712	0.263011336
15	6.61	99.61	14.6	45.09740411	54.51259589	0.272562979
16	6.46	99.61	14.6	44.0740137	55.5359863	0.277679932
17	6.21	99.61	14.6	42.36836301	57.24163699	0.286208185
18	6.01	99.61	14.6	41.00384247	58.60615753	0.293030788
19	5.81	99.61	14.6	39.63932192	59.97067808	0.29985339
20	5.64	99.61	14.6	38.47947945	61.13052055	0.305652603
21	5.4	99.61	14.6	36.84205479	62.76794521	0.313839726
22	5.2	99.61	14.6	35.47753425	64.13246575	0.320662329
23	4.93	99.61	14.6	33.63543151	65.97456849	0.329872842
24	4.64	99.61	14.6	31.65687671	67.95312329	0.339765616
25	4.41	99.61	14.6	30.08767808	69.52232192	0.34761161
26	4.18	99.61	14.6	28.51847945	71.09152055	0.355457603
27	4.03	99.61	14.6	27.49508904	72.11491096	0.360574555
28	3.84	99.61	14.6	26.19879452	73.41120548	0.367056027
29	3.58	99.61	14.6	24.42491781	75.18508219	0.375925411
30	3.42	99.61	14.6	23.33330137	76.27669863	0.381383493
31	3.23	99.61	14.6	22.03700685	77.57299315	0.387864966
32	3.35	99.61	14.6	22.85571918	76.75428082	0.383771404
33	3.4	99.61	14.6	23.19684932	76.41315068	0.382065753

34	3.3	99.61	14.6	23.06039726	76.54960274	0.382748014
35	3.31	99.61	14.6	22.58281507	77.02718493	0.385135925
36	3.37	99.61	14.6	22.99217123	76.61782877	0.383089144
37	3.35	99.61	14.6	22.85571918	76.75428082	0.383771404

APPENDIX B-1: Foaming Tendency Test Results

Stirrer speed	Time, sec				
	29.6wt% DEA Solution	26.7 wt % DEA solution	24.3 wt % DEA solution	22.76 wt % DEA and 6.39 wt % MEA solution	21.83 wt % DEA and 10.231 wt % MEA solution
Speed 1	23.5	20.5	19.5	27.4	32.5
Speed 2	17.4	16.1	15.4	20.5	28.3
Speed 3	13.5	10.5	9.8	17.5	23.4

TABLE F1: Foaming tendency of lean solvent

Stirrer speed	Time, sec				
	29.6wt% DEA Solution	26.7 wt % DEA solution	24.3 wt % DEA solution	22.76 wt % DEA and 6.39 wt % MEA solution	21.83 wt % DEA and 10.231 wt % MEA solution
Speed 1	22.4	18.5	17.5	25.4	31.2
Speed 2	16.4	14.2	14.3	19.5	27.4
Speed 3	13.2	10.7	8.5	16.8	20.4

TABLE F2: Foaming tendency of fat solvent

Stirrer speed	Time, sec				
	29.6wt% DEA Solution	26.7 wt % DEA solution	24.3 wt % DEA solution	22.76 wt % DEA and 6.39 wt % MEA solution	21.83 wt % DEA and 10.231 wt % MEA solution
Speed 1	22.4	18.5	17.5	25.4	31.2
Speed 2	16.4	14.2	14.3	19.5	27.4
Speed 3	13.2	10.7	8.5	16.8	20.4

TABLE F3: Foaming tendency of contaminated fat solvent

APPENDIX C-1: Sample calculation of absorbed CO_2 in the solvent

Let;

A = Outlet CO_2 reading at the initial of the experiment, vol%.

B = Outlet CO_2 reading at the predetermined time, vol %.

Thus,

C = Absorbed CO_2 in the solvent at predetermined time, vol%.

D = CO_2 flowrate at that particular time, ml/min.

Mass flowrate of the CO_2 at that time = D x Density of CO_2 x (1/1000)

= E, kg/min

Mole of CO_2 (flowrate) at that particular time = E / Molecular weight of CO_2

= F, mole/min

Thus,

Amount of CO_2 (Mole) absorbed per ml of solvent

= F/ Solvent flowrate

= Mol of CO_2 / ml of solvent.